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A COMPARISON OF TWO WINTER-TYPE HEAVY RAINFALL EVENTS IN HAWAII KONA STORM AND UPPER-TROPOSPHERIC TROUGH FLASH FLOOD PRODUCERS

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A Comparison of Two Winter-type Heavy Rainfall Events in Hawaii
Kona Storm and Upper-tropospheric Trough
Flash Flood Producers

ABSTRACT

Two winter-time flash flood events that affected the state of Hawaii are reviewed and diagnosed. Both events occurred during the normal winter rainfall season, which has been defined as commencing in October and ending in April. During this period of time, the leeward sections of the Hawaiian Islands experience synoptic conditions which may result in short term reversal of the predominant and steady trade wind flow regime, or in development of upper level tropospheric systems, which provide the destabilization which triggers widespread precipitation in tropical settings. Either of these wintertime scenarios can provide the required meteorological processes that produce much of the annual precipitation.

The two events that will be reviewed and compared for this study occurred during the first few months of 1994. The first included a six day period from February 12 through February 17, while the second spanned a four day period from March 22 through March 25. Both events resulted in rainfall totals of up to 8 inches in the lower elevations of the leewards, and as much as 20 inches being recorded at higher elevations and windward sections of the islands. Although references are made throughout the paper on effects of these two events on the entire Hawaiian island chain, the study has an emphasis which will be primarily centered on the island of Oahu.

The heavy rainfall which fell in a four to six day period challenged forecasters responsible for issuing timely, site-specific, and accurate warnings required for flash flood prone areas. While both events show similarities, the investigation identifies synoptic scale and mesoscale features which account for slightly dissimilar heavy rainfall occurrences. An attempt was additionally made to compare new technological outputs with observed hydrological data.

1. INTRODUCTION

The winter season in the Pacific has previously been defined by Schroeder (1977) as encompassing the months from October through April. Referencing Blumenstock and Price (1967), Schroeder further describes the typical synoptic scale features which are responsible for triggering large scale rainfall, with Kona lows, upper tropospheric troughs or closed lows, and cold fronts, falling within the list of potential "wintertime" flash flood producers.

"Wintertime" is the period of time when the Hawaiian Islands historically replenish a large majority of the fresh water supply that is required for island use and consumption throughout the year. Below normal winter rainfall certainly results in a need to impose extreme water management measures aimed at avoiding drought problems, which can last for many months. Once the winter season ends, the Hawaiian islands must rely on weak tropical cyclones during the summer months to replenish fresh water in low capacity watersheds used throughout the Hawaiian Islands. Appendix A provides a reference map of Hawaii.

Two heavy rainfall flash-flood events that were beneficial in replenishing the water supply, but disrupted daily activities and resulted in several fatalities due to drowning throughout the state of Hawaii, occurred during the first quarter of the 1994 calendar year.

The first event occurred during February 12-17, 1994, with heaviest precipitation accounting for rainfall totals of 4-8 inches over the normally dry leeward sections, and 15-20 inches over high mountainous terrain and windward sides of the islands. Most of the rainfall was recorded over the northern parts of the islands, with Maui and the big island of Hawaii (hereafter referred to as the "Big Island") receiving the majority of their rainfall on the last day of the event.

The second event, which occurred a little over a month later (March 22-25, 1994), spared only Kauai, as heavy rainfall occurred throughout the remaining Hawaiian Islands. The topography of Hawaii, which has terrain that climbs to 2-4 thousand feet through most of the islands and to almost 14 thousand feet over the Big Island, contributed to quick runoff which adversely impacted many heavily travelled roads.

Both events had very similar rainfall patterns, but were produced by two different synoptic scale systems. They will be analyzed separately, then will be compared to show the distinctive characteristics, which tell them apart. Isohyet maps will be presented which show the similarities in total rainfall reported with each event. While leeward sections of the islands normally receive light rainfall daily, the addition of significant synoptic scale forcing can result in the production of excessive rainfall amounts occurring in those normally drier areas also.

2. DATA SOURCES

National Meteorological Center (NMC) products received on the Weather Service Forecast Office (WSFO) MARTA graphics display system were used as the principal synoptic charts.

Computer plotted soundings for both Lihue, Kauai, and for Hilo, Hawaii, and time section wind profiles for those two stations were also used.

The rainfall network used for this study contains data from the normal 24-hour reporting surface observation sites. These are the Weather Service Offices at Lihue, Kauai; Honolulu, Oahu; Kahului, Maui; and Hilo, Hawaii. In addition, rainfall received on the Hydrological Network (HydroNet) Computer from the sixty-five (65) Limited Automatic Remote Collection (LARC) locations throughout the Hawaiian Islands were used. There are eight (8) LARCs on Kauai, 28 on Oahu, 2 on Molokai, 1 on Lanai, 10 on Maui, and 16 on the Big Island of Hawaii.

Geostationary Operational Environmental Satellite (GOES-7) data was also reviewed.

Finally, the Weather Surveillance Radar - 1988 Doppler (WSR-88D) located at Molokai, had just been installed (January 1994) and any data that was being received at the WSFO Principal User Processor (PUP) was used in a test and training mode. The WSR-88D was unable to archive the data for the entire event, because mechanical problems occurred shortly after it was "accepted".

3. KONA STORM ENVIRONMENT DEFINITION

Papers have previously been written to document the synoptic-scale features used to identify Kona storms. However, surprisingly few studies focusing on the occurrence of this important flash flood producing phenomena can be found.

Perhaps one of the first references in the literature that provided a climatological definition dates back to 1914 by Daingerfield (1921). In his discussion, the root for the word "Kona" is explained as simply coming from the Polynesian/native Hawaiian language in the early 1900s to relate to the leeward sections of the islands. Therefore, any heavy precipitation event which occurred over the leewards came to be identified as a Kona storm.

In his review of meteorological conditions that were present, Daingerfield was limited to surface data. However, his observations and first impressions remarkably provided initial facts which explained the cause of the development of systems in low level south and southwest flow. Daingerfield determined that the storm responsible for producing heavy rainfall normally lasted 3-4 days.

It was not until Simpson's (1951) study, that the vertical structure of the Kona cyclone became better understood. Simpson described the event as a cold core low of large size and dominant importance to circulations in the middle and upper troposphere and normally nested south of a relatively warm ridge of high pressure. Therefore, relying on the pioneers who investigated the Kona storm conditions, we can identify/define the event as one where:

a) Surface low circulation develops to the west of the Hawaiian Islands
b) Reversal of low level wind occurs- trade winds become south and southwest
c) A heavy rainfall event which usually lasts 3-4 days

It will be shown in the following discussion that the above mentioned conditions developed over Hawaii in February 1994 and resulted in widespread precipitation, which caused flooding of low lying areas. The event caused flash flood conditions over the north part of the island of Oahu. During the beginning of the event, a boy scout who was returning from a weekend camp-out cut short by rain, drowned. Additionally, several traffic accidents and minor injuries occurred on H-1 and H-2 freeways and on the Likelike Highway. Other consequences of the heavy rains were mudslides, flooded homes, and debris jamming, which created damming on bridges.

4. FEBRUARY 12-17, 1994 EVENT - KONA STORM

On Thursday, February 10, 1994 at 2 pm Hawaii local time (0000UTC, Friday), surface analysis indicated a 1035 mb High centered near its normal location just north of 40N and just east of 150W. Trade wind flow across the southern portion of the High extended west through Hawaii. However, a perturbation was noted in the vicinity of Johnston Island, the first evidence of an inverted trough embedded in the southwest portion of the high. Meanwhile, a 998 mb Low centered near 57N 160W continued to move slowly to the southeast.

By Saturday, February 12, 1994, the Kona storm event was well into its formative stage. Tragically, even before the heavy rains commenced, an 11-year old cub scout was swept away and drowned when the Laie-Maloo Stream (north Oahu) became swollen at approximately 8:45 am. In reviewing the rainfall data from the closest LARC (see **Appendix B** for background map of Oahu LARC locations), the recorded fifteen minute rainfall data did not show a large amount of rain falling in one place between the hours of 7:00 am and 9:00 am. Rainfall amounts for that period of time follow:

Punaluu Pump (HI-03)..15-minute rainfall data...Feb. 12, 1994									
Time	7:00	7:15	7:30	7:45	8:00	8:15	8:30	8:45	9:00
Rain	0.02	0.01	0.02	0.09	0.27	0.30	0.51	0.67	0.24
24-hour rainfall total for Saturday, February 12, 1994 was 3.64 inches									

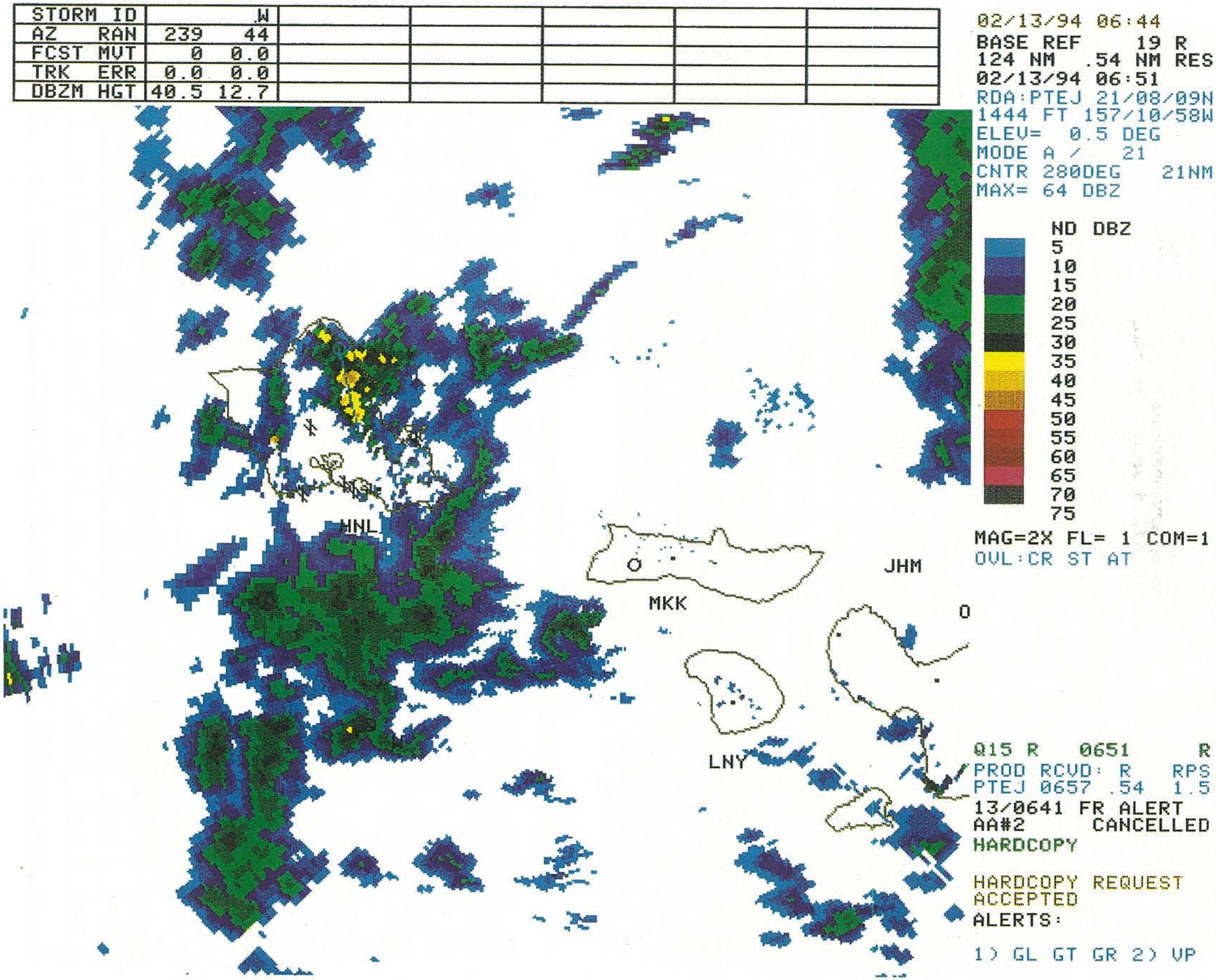


Figure 1
MOLOKAI, HI WSR-88D ..... Base Reflectivity (02/13/94 - 06:41Z)
(Note: System clock was 10 minutes fast)

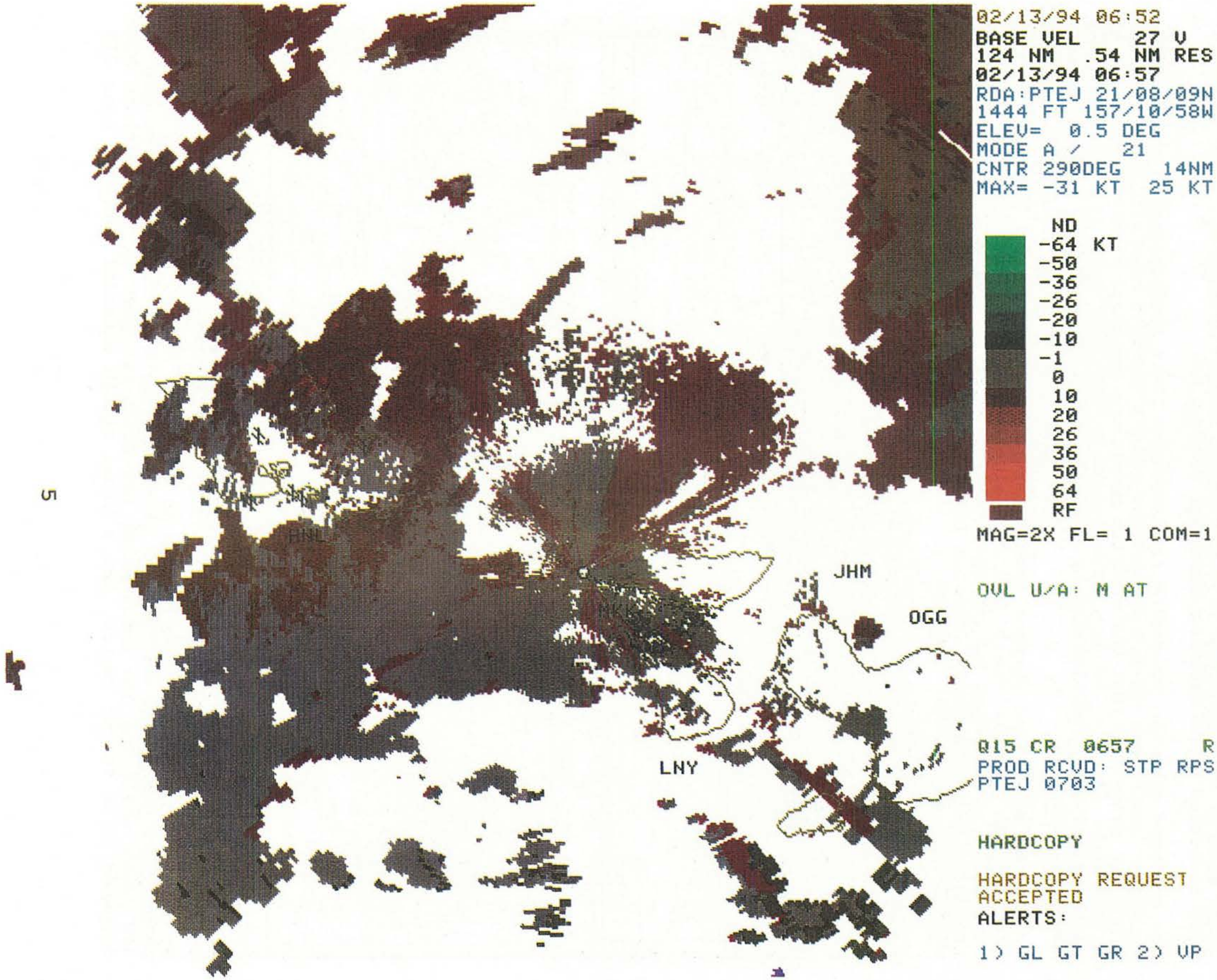


Figure 2
MOLOKAI, HI WSR-88D ..... Base Velocity (02/13/94 - 06:47Z)
(Note: System clock was 10 minutes fast)

By Saturday evening (0641 UTC, Sunday), the Molokai WSR-88D 0.5 degree elevation angle base reflectivity data indicated numerous areas where the reflectivity of the storms was of 35-45 dBz over the north Koolau Range. At the same time, reflectivity pockets of 40 dBz were found over the leeward sections of Oahu. A large area of rain was south of Oahu over the Pacific (**Figure 1**). Base velocity data indicated winds becoming southeast (**Figure 2**).

The synoptic maps for the period from February 13-14 are presented, since these represent conditions which triggered the event's heaviest rainfall. In this case study, it is evident that the synoptic conditions are quite similar to Simpson's (1951) case study of January 1949, where a deepening wave cyclone, located northwest of Hawaii was blocked by a migratory anticyclone which was eventually displaced east.

Figure 3a shows that surface high pressure to the north of Johnston Island between 35N and 50N was blocking a significant baroclinic zone which was attempting to move east out of the northwest Pacific. Meanwhile, the inverted trough in the vicinity of Johnston Island was becoming better defined and was exhibiting cyclogenetic features.

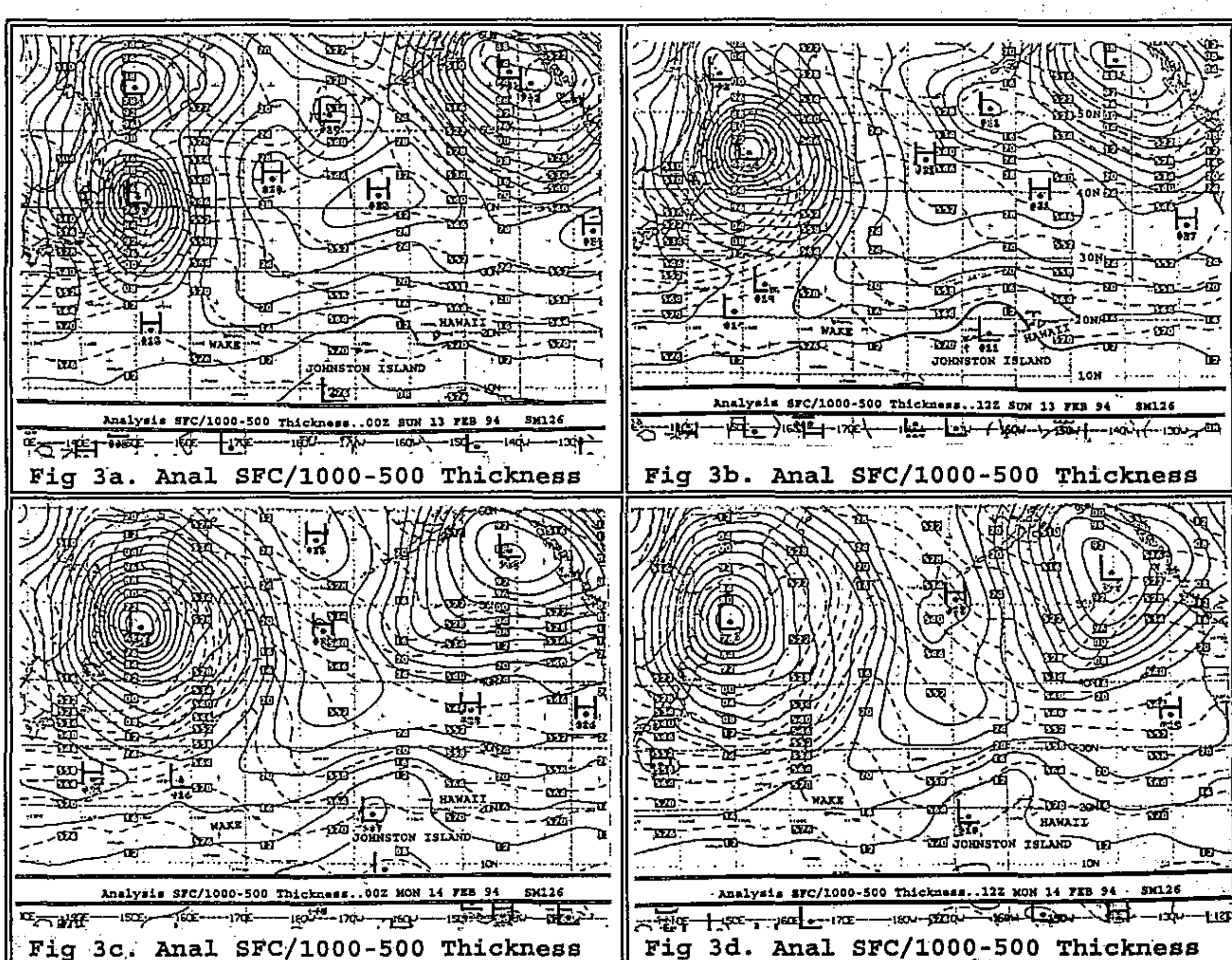


Fig 3a. Anal SFC/1000-500 Thickness

Fig 3b. Anal SFC/1000-500 Thickness

Fig 3c. Anal SFC/1000-500 Thickness

Fig 3d. Anal SFC/1000-500 Thickness

By Sunday, February 13, 1994 - Figure 3b (1200 UTC, Sunday), the surface high was holding its ground and was centered almost due north of the Hawaiian Islands at 40N 156W, while the low approaching the northwest part of the mainland had deepened to a 986 mb center, and a broad trough extended south to near 35N between 148W and 120W. The NMC global spectral model indicated a 1011 mb Low to the west of the Hawaiian Islands at 18N 165W. This low had initially been detected in an NMC surface analysis, which had been hand drawn at 0600 UTC Sunday, February 13, 1994 (not shown), indicating a low with a trough extending south was located to the west of the Hawaiian Islands.

On February 14, 1994 at 0000 UTC (2 pm Sunday), the low had become a closed circulation over Johnston Island and steady rainfall commenced over the Hawaiian Islands. Twenty-four hour rainfall amounts were generally 1-2 inches with locally heavier amounts of 3-4 inches. An isolated maximum amount of 7.41 inches was recorded in Oahu. This was followed by an additional 2-3 inches of rainfall on Monday.

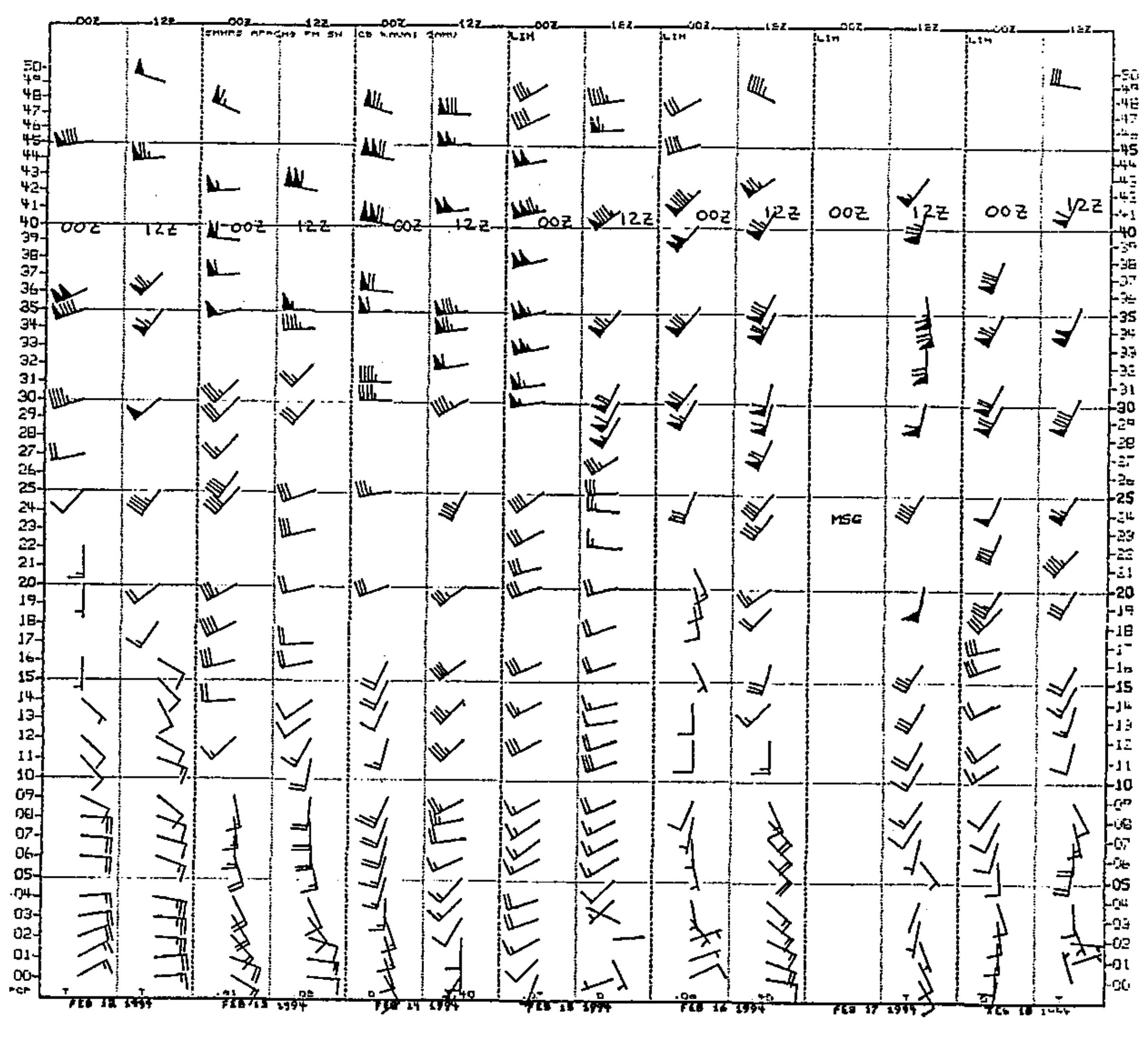
Table 1
Rainfall data from 0100 to 0100 HST

February 1-28, 1994	[illegible]	[illegible]	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
KAUAI																														
48 ANAHOLA	7.25	9.45	.00	.04	.22	.00	.00	.00	.02	.01	.70	.06	.01	.42	1.52	.02	1.93	1.38	.01	.00	.06	.03	.00	.02	.04	.17	.00	.55	.00	.00
45 HANALEI	12.97	19.09	.00	.00	.75	.11	.17	.01	.07	.15	.01	.65	.57	4.82	1.11	.00	1.45	2.72	.00	.03	.00	.02	.01	.01	.01	.29	.00	.00	.00	.00
49 HANAPEPE	4.94	6.13	.00	.00	.13	.06	.00	.00	.00	.01	.00	.00	.01	.49	2.21	.01	.79	1.06	.00	.11	.00	.00	.00	.06	.00	.00	.00	.00	.00	.00
43 KALAHEO	6.52	9.56	.00	.01	.59	.16	.05	.00	.06	.08	.00	.08	.58	.49	2.27	.03	.83	1.14	.04	.03	.00	.00	.01	.05	.00	.01	.00	.01	.00	.00
50 KAPAHI	12.74	21.48	.00	.09	.15	.20	.06	.00	.07	.04	.66	.71	.22	1.05	4.47	.01	1.49	3.60	.06	.03	.22	.19	.00	.00	.00	.00	....	....	.05	.00
46 KOKEE	2.97	8.31	.00	.00	.42	.34	.00	.00	.00	.14	.00	.23	.01	1.12	.10	.01	.04	.01	.07	.13	.01	.00	.02	.31	.00	.01	.02	.00	.00	.00
40 WAILUA	9.63	15.72	.00	.00	.16	.17	.08	.00	.06	.01	.10	1.01	.16	1.40	1.78	.00	1.08	2.92	.00	.00	.18	.02	.01	.05	.19	.11	.19	.00	.00	.00
41 WAINIHA	9.66	19.50	.00	.00	1.10	.38	.49	.00	.01	.16	.00	.79	.23	2.78	.85	.00	.70	1.56	.02	.03	.04	.00	.00	.00	.05	.19	.00	.00	.00	.00
OAHU																														
16 AHUIMANU LOOP	23.96	37.47	.00	.00	.37	.15	.02	.01	.03	.02	1.22	.10	.09	2.87	2.32	2.86	9.86	1.99	.37	.00	.21	.00	.05	.00	.15	.13	.95	.13	.00	.00
26 ALOHA TOWER	6.17	7.43	.00	.00	.00	.05	.02	.02	.00	.00	.00	.04	.03	.09	1.15	2.69	.87	.62	.43	.01	.00	.13	.00	.00	.00	.00	.01	.01	.00	.00
10 HAKIPUU MAUKA	2.65	10.02	.00	.00	.28	.06	.10	.02	.00	.01	.11	....	....	....	....	....	....	....	.27	.00	.59	.07	.00	.00	.15	.09	.90	.00	.00	.00
21 HAWAII KAI	5.51	7.97	.02	.00	.03	.01	.01	.03	.00	.00	.00	.00	.00	.02	.65	2.84	.63	.40	.45	.01	.11	.00	.00	.00	.10	.00	.00	.00	.00	.00
09 KAHUKU	7.15	9.04	....	....	.08	.06	.02	.00	.00	.00	.38	.01	.00	1.54	1.48	.96	.79	1.07	.06	.00	.00	.07	.00	.14	.18	.00	.30	.01	.00	.00
28 KAMEHAME	5.95	9.25	.00	.00	.01	.01	.04	.04	.00	.00	.00	.00	.00	.06	.68	2.76	1.00	.33	.39	.01	.27	.01	.00	.00	.29	.00	.06	.00	.00	.00
12 KUNIA SUBSTN	7.69	8.51	.00	.00	.04	.00	.00	.00	.00	.00	.53	.00	.00	.60	2.20	2.44	.54	1.10	.20	.00	.00	.00	.05	.00	.00	.00	.09	.04	.09	.00
95 LUALUALEI	8.03	8.90	.00	.01	.03	.03	.00	.01	.00	.01	.09	.01	.00	.39	2.22	2.81	.25	1.77	.20	.12	.06	.02	.02	.02	.00	.00	.00	.00	.00	.00
15 LULUKU	14.54	23.71	.00	.00	.58	.19	.07	.06	.01	.06	.53	.43	.10	1.71	1.54	3.22	3.48	.90	.36	.01	.01	.03	.01	.00	.12	.11	.99	.04	.01	.01
19 MANOA LYON ARBO	14.36	30.06	.00	.00	1.19	.01	.23	.95	.21	1.11	.32	.89	1.23	1.07	1.08	2.48	.74	.49	.48	.01	.00	.18	.08	.00	.01	.02	.41	1.11	.00	.00
22 MAUNAWILI	13.91	24.65	.03	.01	.24	.20	.07	.10	.01	.03	2.20	.23	.06	.74	1.56	2.98	2.05	.85	.51	.02	.03	.18	.06	.05	.10	.08	1.42	.11	.02	.00
14 MILILANI	8.04	8.81	.00	.00	.26	.02	.00	.01	.06	.00	.12	.13	.29	.75	1.93	2.42	.56	1.08	.20	.00	.00	.05	.03	.00	.00	.00	.09	.04	.00	.00
19 MOANALUA	8.58	11.95	.00	.00	.85	.41	.10	.07	.06	.13	.03	.26	.60	.88	1.27	2.38	.52	.73	.32	.00	.00	.00	.12	.00	.11	.00	.02	.02	.00	.00
06 NIU VALLEY	7.04	12.71	.00	.00	.12	.20	.12	....	....	.01	.03	.03	.00	.45	.95	2.97	.65	.52	.43	.01	.02	.07	.00	.00	.03	.02	.35	.04	.01	.00
20 NUUANU WATERSUP	12.73	22.92	.00	.00	.92	.86	.42	.23	.21	.53	.17	1.12	1.35	.95	1.09	3.00	.57	.54	.43	.01	.00	.04	.01	.00	.01	.04	.13	.10	.00	.01
24 OLAMANA	10.59	16.41	.00	.00	.07	.13	.00	.01	.00	.00	.04	.09	.00	.79	1.40	3.10	2.35	.70	.42	.00	.00	.05	.00	.00	.15	.11	1.18	.00	.00	.00
11 PALISADES	8.58	11.90	.00	.00	.77	.30	.05	.04	.08	.03	.06	.21	.61	.83	1.61	1.91	.78	.87	.32	.00	.00	.02	.01	.00	.01	.00	.05	.02	.00	.00
25 PALOLO F.S.	8.13	13.93	.00	.01	.23	.28	.27	.18	.01	.06	.00	.25	.49	.16	.99	2.76	.71	.45	.49	.00	.00	.52	.03	.02	.00	.00	.16	.06	.00	.00
07 POAMOHO	9.44	11.74	.00	.00	.05	.00	.00	.05	.01	.00	.04	.03	.04	1.28	2.65	2.46	.16	2.22	.22	.01	.00	.05	.00	.10	.06	.00	.00	.01	.00	.00
03 PUNALUU PUMP	18.16	23.70	.00	.00	.10	.08	.01	.09	.02	.01	1.03	.02	.01	3.64	7.41	1.99	.00	.72	.21	.00	.08	.44	.01	.01	.33	.03	1.89	.03	.00	.00
04 WAIALUA	6.69	8.49	.00	.00	.03	.01	.01	.04	.00	.00	.01	.00	.01	.99	1.66	1.44	.42	1.87	.17	.00	.00	.00	.00	....	.00	.00	.00	.01	.00	.00
17 WAIANAE KAWIWI	7.49	7.94	.00	.00	.00	.00	.00	.00	.07	.00	.00	.00	.00	.63	1.62	1.83	.27	2.39	.21	.16	.01	.14	.07	.02	.01	.00	.00	.00	.00	.00
29 WAIAWA	7.92	10.39	.00	.00	.57	.14	.06	.10	.07	.02	.07	.30	.30	.78	1.79	1.70	.79	.74	.28	.01	.00	.12	.01	.01	.00	.01	.04	.01	.00	.00
30 WAIHEE PUMP	20.29	30.04	.00	.00	.51	.20	.02	.03	.00	.26	1.70	.14	.20	3.08	2.07	2.40	6.69	1.66	.00	.00	.00	.00	.00	.00	.17	.09	1.03	.04	.00	.00
13 WAIMANALO	7.58	12.49	.00	.00	.02	.08	.05	.04	.00	.00	.00	.00	.00	.33	.89	3.90	1.32	.51	.43	....	....	....	....	....	....	....	....	....	.00	.01
08 WAIPIO	5.05	6.04	.00	.00	.08	.00	.01	.02	.01	.00	.14	.01	.02	.71	.17	3.62	.13	.08	.00	.00	.01	.02	.01	.00	.01	.00	.00	.00	.00	.00
02 WHEELER AFS	3.67	4.56	.00	.00	.28	.01	.04	.02	.01	.00	.15	.02	.22	.40	1.06	1.18	.23	....	....	.01	.00	.00	.00	.03	.00	.00	....	.01	.00	.00
27 WILSON TUNNEL	14.35	27.75	.00	.00	.78	.33	.13	.17	.04	.17	.64	.55	.29	1.46	1.13	3.20	2.65	.56	.38	.01	.00	.07	.02	.00	.06	.12	.91	.28	.00	.00
MOLOKAI																														
71 KAUNAKAKAI XXX	3.75	3.96	.01	.00	.00	.00	.00	.00	.01	.00	.00	.01	.00	.01	.01	1.78	.52	.06	1.20	.00	.00	.07	.00	.00	.03	.01	.01	.00	.01	.01
73 MOHOLO	4.23	5.06	.02	.07	.19	.30	.06	.06	.04	.08	.17	.29	.07	.04	.04	1.82	.00	.01	.82	.01	.02	.02	.02	.01	.01	.01	.02	.01	.01	.01
LANAI																														
72 LANAI CITY	5.82	7.29	.00	.00	.17	.00	.00	.00	.00	.00	.00	.53	.07	.19	.01	3.69	.49	.08	.56	.00	.01	.01	.00	.00	.00	.00	.00	.00	.00	.01
MAUI																														
63 HAIKU	.43	1.17	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	.00	.62	.00	.10	.00	.00	.00	.06	.11	.04	.00	.00	.00
61 HANA	12.62	23.52	.04	.19	.43	.50	.27	.00	.04	.30	1.20	.40	.17	1.16	4.36	.39	.71	1.39	.57	.01	.00	.00	.00	.00	.25	.19	.04	.00	.01	.00
74 KAHAKULOA	.02	.02	....	....	....	....	....	....	....	....	....	....	....	....	.02	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
75 KIHEI-2	2.21	2.77	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.07	.00	.84	.39	.01	.28	.00	.62	.00	.00	.00	.00	.03	.00	.00	.00	.00
55 KULA	4.20	5.38	.00	.00	.00	.00	.00	.00	.00	.00	.01	.53	.00	.22	.00	.85	1.44	.03	.68	.00	.22	.00	.00	.00	.00	.00	.21	.03	.15	.00
52 MAHINAHINA	5.19	8.42	.00	.07	.37	.77	.29	.13	.15	.02	.00	.25	.21	.25	.00	1.68	.16	.02	.28	.04	.49	.00	.00	.00	.00	.00	.00	.00	.00	.00
70 PUKALANI	3.95	7.15	.00	.00	.03	.91	.20	.00	.00	.00	.00	.29	.00	.20	.00	.61	.36	.02	1.07	.01	.16	.00	.00	.00	.04	.01	.00	.00	.04	.00
64 ULUPALAKUA	3.90	5.07	.01	.00	.00	.00	.00	.00	.00	.00	.00	.00	.01	.10	.00	1.05	.41	.01	1.05	.02	.87	.01	.00	.00	.00	.22	.05	.07	.02	.00
76 WAIKAPU CC	3.00	5.87	.00	.02	.05	.00	.05	.01	.00	.00	.00	.00	.00	.11	.00	1.30	.35	.00	.54	.00	.55	.00	.00	.00	.00	.00	.00	.02	.00	.00
65 WAILUKU	2.78	5.72	.00	.00	.16	.00	....	.03	.00	.00	.00	.00	.00	.04	.00	1.03	.29	.04	.35	.35	.46	.01	.00	.00	.02	.00	.00	.00	.00	.00
HAWAII																														
94 GLENWOOD	23.51	32.97	.15	.01	.52	1.79	1.28	.33	.49	.81	1.66	3.31	.99	.92	.01	.11	.29	1.17	7.48	.48	.01	.03	.00	.00	.08	.32	1.09	.38	.00	.00
35 HONAUNAU-2	2.61	4.17	.00	.00	.00	.04	.09	.00	.00	.00	.01	.00	.00	.08	.00	.42	.36	.05	1.54	.00	.00	.00	.00	.00	.00	.00	.00	.02	.00	.00
87 HONOKAA	8.38	23.19	.00	.00	.46	1.04	2.50	.57	.22	.00	.00	.07	.01	.11	.00	.32	.31	.01	.18	.33	.22	.02	.00	.00	.03	1.25	.45	.28	.00	.00
96 KAHUA RANCH	5.17	10.96	.00	.02	.17	.64	.35	.16	.16	.01	.03	.33	.08	.08	.02	1.46	.46	.10	.77	.24	.17	.06	.00	.00	.00	.24	.03	.03	.00	.01
30 KAPAKOA	2.45	4.17	.00	.00	.00	.00	.00	.00	.00	.00	.00	.04	.00	.06	.00	.50	.38	.05	1.14	.01	.27	.00	.00	.00	.00	.00	.00	.00	.00	.00
26 KAMUELA	2.52	5.35	.00	.02	.25	.11	.25	....	....	....	....	....	....	.07	.00	.54	.40	.08	.26	.03	.01	.00	.00	.00	.00	.21	.13	.10	.00	.00
37 KAMUELA UPPER	5.90	13.05	.01	.05	.65	.35	.77	.47	.27	.06	.03	.24	.55	.09	.00	.56	.38	.12	.44	.03	.08	.01	.00	.00	.00	.03	.15	.11	.03	.00
34 KEALAKEKUA	2.09	3.00	.02	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.05	.00	.50	.52	.05	.91	.00	.00	.00	.00	.00	.00	.00	.00	.01	.00	.00
80 LAUPAHOEHOE	15.14	36.32	.00	.01	.37	1.06	1.89	.20	.82	.33	.03	2.24	1.89	.35	.01	.06	.10	.05	2.77	.03	.02	.55	.00	.00	.43	.54	1.08	.25	.00	.00
81 MOUNTAIN VIEW	20.26	26.80	.08	.02	.30	1.40	.89	.10	.48	.52	1.27	4.45	1.53	1.36	.00	.03	.08	.36	5.72	.37	.00	.00	.00	.00	.05	.15	.25	.35	.08	.00
85 PAHALA	6.45	9.58	.00	.00	.00	.01	.00	.00	.00	.00	.56	.85	.00	.30	.68	.53	.33	2.04	....	....	.00	.00	.00	.00	1.10	.04	.02	.01	.00	.58
33 PAHOA	27.63	39.13	.21	.08	.26	1.20	.95	.20	.83	1.14	4.45	.19	1.15	4.14	1.43	.09	.21	.65	8.56	.68	.00	.00	.00	.00	.26	.43	.33	.06	.00	.07
91 PIIHONUA	22.79	31.47	.00	.00	.75	2.06	1.23	.20	.46	.83	1.10	1.54	2.24	1.19	.31	.27	.11	.53	6.66	.28	.23	.45	.00	.00	.09	.18	1.47	.57	.01	.00
39 UPOLU AIRPORT	4.76	8.27	.00	.00	.04	.69	.58	.04	.43	.14	.16	.04	.25	.03	.02	1.24	.18	.05	.46	.15	.10	.02	.00	.00	.00	.00	.02	.05	.00	.00
82 WAIAHA	3.46	4.85	.00	.00	.00	.01	.00	.00	.00	.00	.00	.00	.00	1.32	.00	.55	.74	.02	.81	.01	.00	.00	.00	.00	.00	.00	.00	.09	.00	.00
92 WAIAKEA UKA	26.77	37.18	.01	.00	.72	2.14	1.25	.06	.32	.99	.90	2.81	1.87	1.44	.89	.25	.12	.43	6.43	.80	.15	2.81	.00	.00	.16	.29	1.41	.45	.00	.01
MAX 24 HOUR VALUE =			.21	.19	1.19	2.14	2.50	.95	.83	1.14	4.45	4.46	2.24	4.82	7.41	3.90	9.86	3.60	8.56	.80	.87	2.81	.12	.31	1.10	1.25	1.89	1.11	.15	.58

Table 1 shows the daily rainfall totals as recorded by the LARC network throughout Hawaii. Rainfall records indicate that the first eleven days of February 1994 were rather dry. A dramatic increase in rainfall is evident throughout Hawaii beginning on February 12, 1994, which tapered off around February 17, 1994.

Figure 4 is a time section of the vertical wind profile for Lihue, Kauai, where the shift from moderate trades at the lower levels, to south and southwest winds is readily evident.

Figure 4
Lihue, Kauai time section plot



February 12-18, 1994

The shift to southerly winds coincides with the time when the heavier rainfall occurred throughout Hawaii, and the end of the event is also seen with the return to trade winds on February 16-17th.

Although only 0000 UTC and 1200 UTC radiosonde data was available to identify the wind shift for this and previous events, the installation of the WSR-88D on Kauai in July 1994 will dramatically increase the volume of vertical wind profile data. The increase in frequency (every 5-6 minutes) should help forecasters to identify the initiation of heavy rainfall.

In examining conditions aloft, it is clear that a Kona cyclone environment developed and triggered the widespread rainfall. Simpson stated that in a Kona environment, a trough at 700-mb in the polar westerlies normally protrudes south of 20N and eventually produces a small closed cyclonic circulation just southwest of Hawaii.

Figures 5a-d indeed shows a trough near 40N 150W which breaks through the weak ridge near 30N by 1200 UTC Monday. However, in this case a closed Low with abundant moisture from Johnston Island east to Hawaii was in place as early as Saturday afternoon (00 UTC Sunday), a good 36 hours before the northern trough protruded southwest into the area west of the Hawaiian Islands.

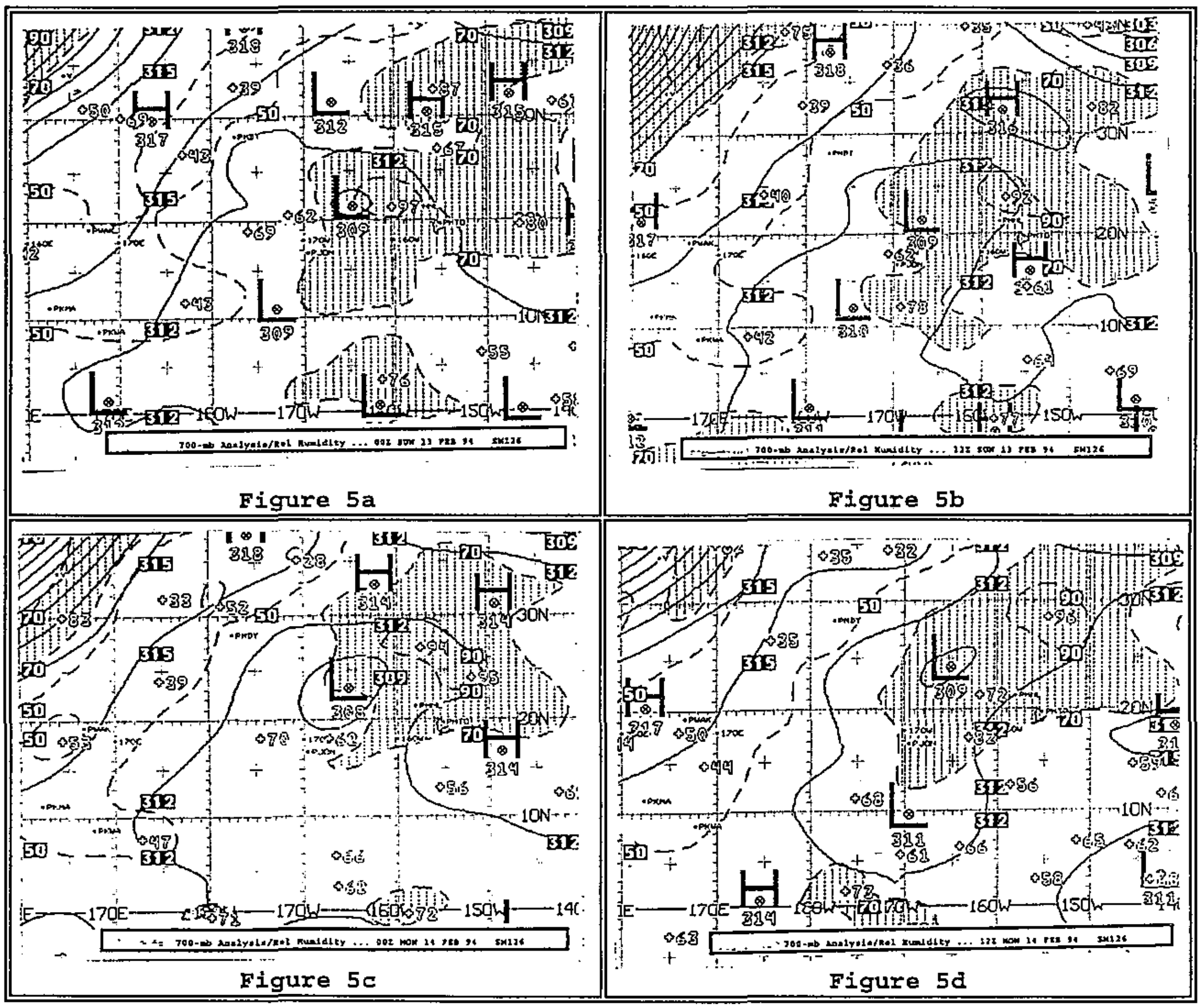


Figure 5a

Figure 5b

Figure 5c

Figure 5d

Winds at 700-mb at Lihue were southerly at 10 knots at 0000 UTC on February 13th. By 1200 UTC on February 14th, the gradient had tightened and the winds at Lihue at 10,000 feet increased to 30 knots. An NMC streamline analysis (not shown) indicated an area of strong confluence between 15N and 25N and 155W and 165W. Destabilization of the lower layers to the west of the Hawaiian Islands was also evident as the temperatures within the confluence corridor were between 4 and 6 degrees Celsius while east of 155W and west of 165W the temperatures were close to 10 degrees Celsius.

At 500-mb, a low, centered near 31N 162W at 0000 UTC on February 13th, drifted southwest to near 23N 174W by 1200 UTC on February 14th (**Figures 6a-d**). The short wave troughs provided an avenue for transporting pockets of colder air across the Johnston Island area. This served to destabilize the rich moisture laden atmosphere to the west of Hawaii.

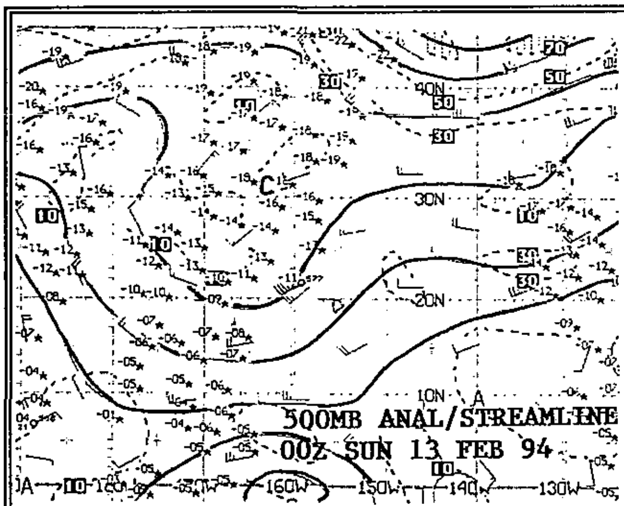


Figure 6a

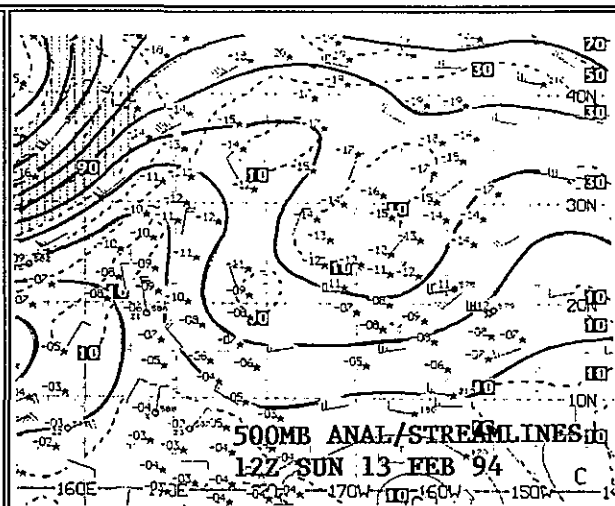


Figure 6b

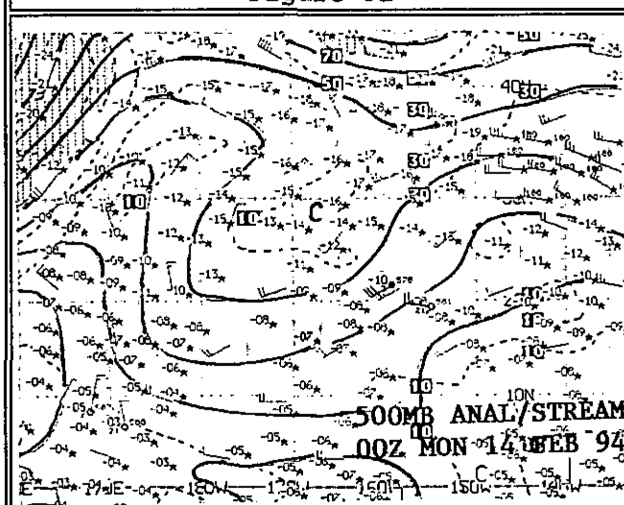


Figure 6c

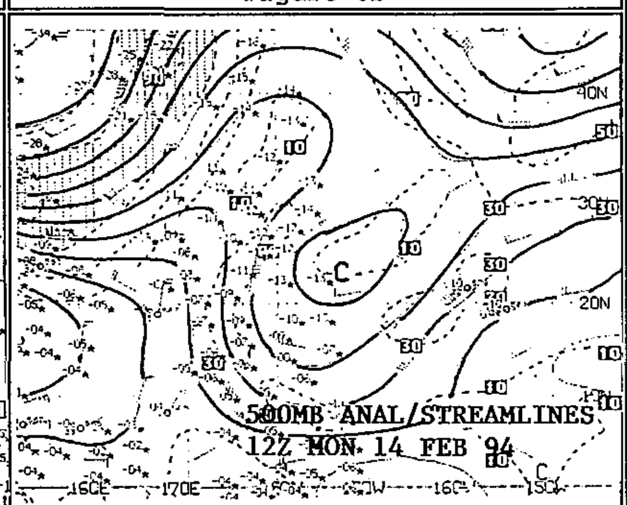


Figure 6d

A closed cyclonic circulation is also noted by 1200 UTC on February 14th. Northerly winds advected cooler air to the bottom of the trough, which by this time extended south to about 8N. Note that in the area to the southwest of the Hawaiian Islands, temperatures were -7 to -8 degrees Celsius in the vicinity of Johnston Island in Figure 6a, and were several degrees lower by Figure 6d. In the tropics, a decrease of only 1 to 2 degrees Celsius can result in a significant change on the stability of the vertical layer. In this case, the dynamic forcing, resulting from such a change, produced a large area of showers and thunderstorms, which then moved northeast into the leeward sections of Hawaii.

Ramage (1971) noted that the middle troposphere is the layer of largest pressure gradients, strongest winds, and greatest convergence in a Kona environment. This was certainly the case for this event.

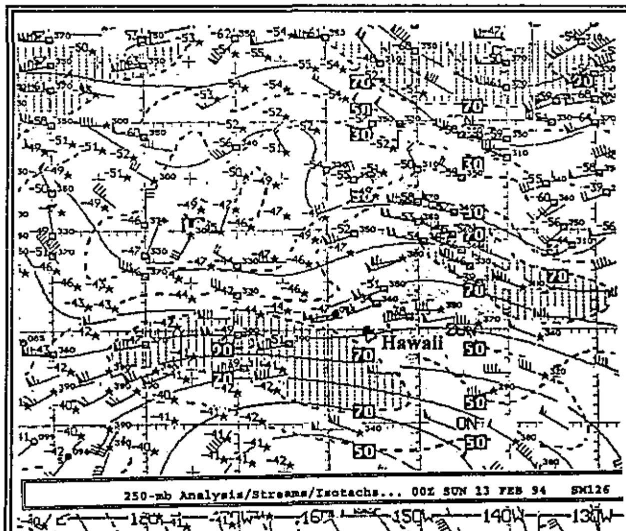


Figure 7a

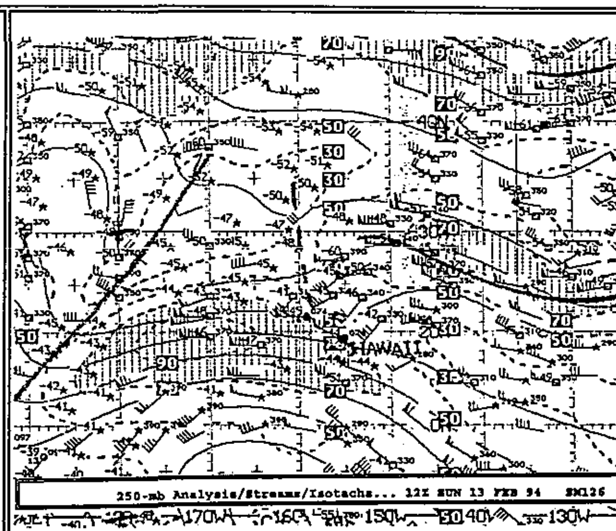


Figure 7b

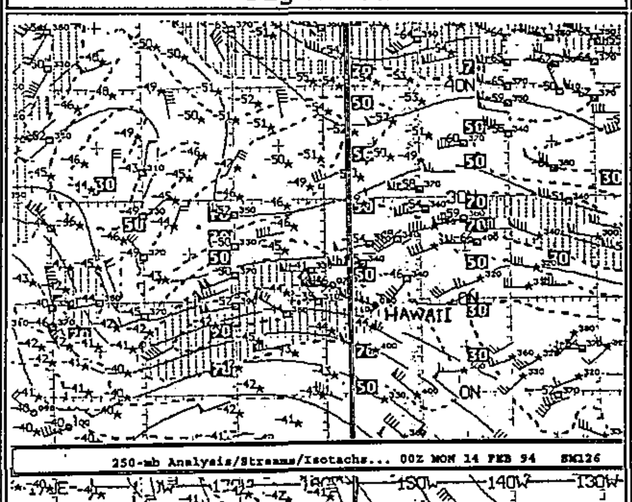


Figure 7c

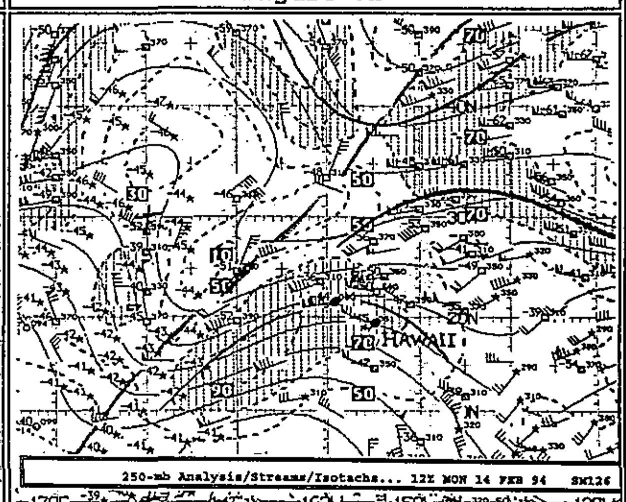


Figure 7d

An area that needs more in-depth study is the synoptic conditions that exist at the jetstream level. Figures 7a-d provide the 250-mb NMC analysis with shaded areas indicating areas of strong winds. Although it is known that jet streaks provide a controlling influence for precipitation processes that occur within mesoscale domains, studies to substantiate the extent of this influence in the tropics are lacking.

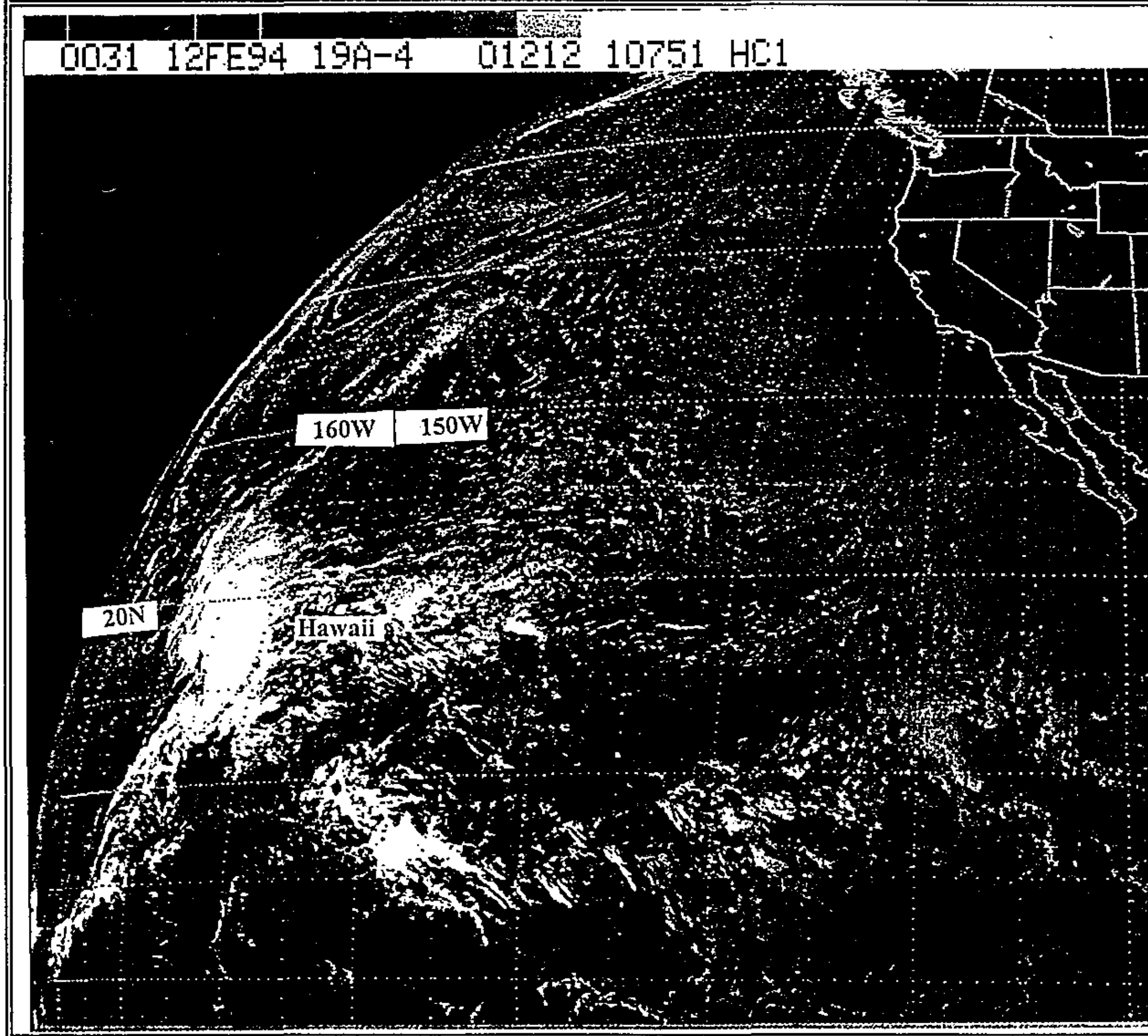
The February event contained a jetstream flow with winds of 80-100 knots in the vicinity of 170W on February 13th. This flow moved toward Hawaii by 1200 UTC on

February 14th where it can be seen that Lihue, Hawaii experienced 100 knot winds. It is clear that the northern Hawaiian Islands were in the left-front portion of the jetstreak, where cyclonic vorticity advection is strongest. The direct thermal circulation and resulting ageostrophic wind was also supportive of synoptic-scale lifting in this region. Therefore, forcing created as the jet moved over Hawaii resulted in the enhancement of rainfall.

In the future, a more detailed examination will likely be done of jetstream interactions as the new gridpoint workstations are used to diagnose vertical motions over tropical regions.

Two satellite photographs are provided in Figures 8 and 9, showing the pre-initiation of the Kona storm on February 12th, and the February 14th initial condition when heavy rains began to move into Hawaii.

Figure 8
GOES-7 SATELLITE PHOTOGRAPH

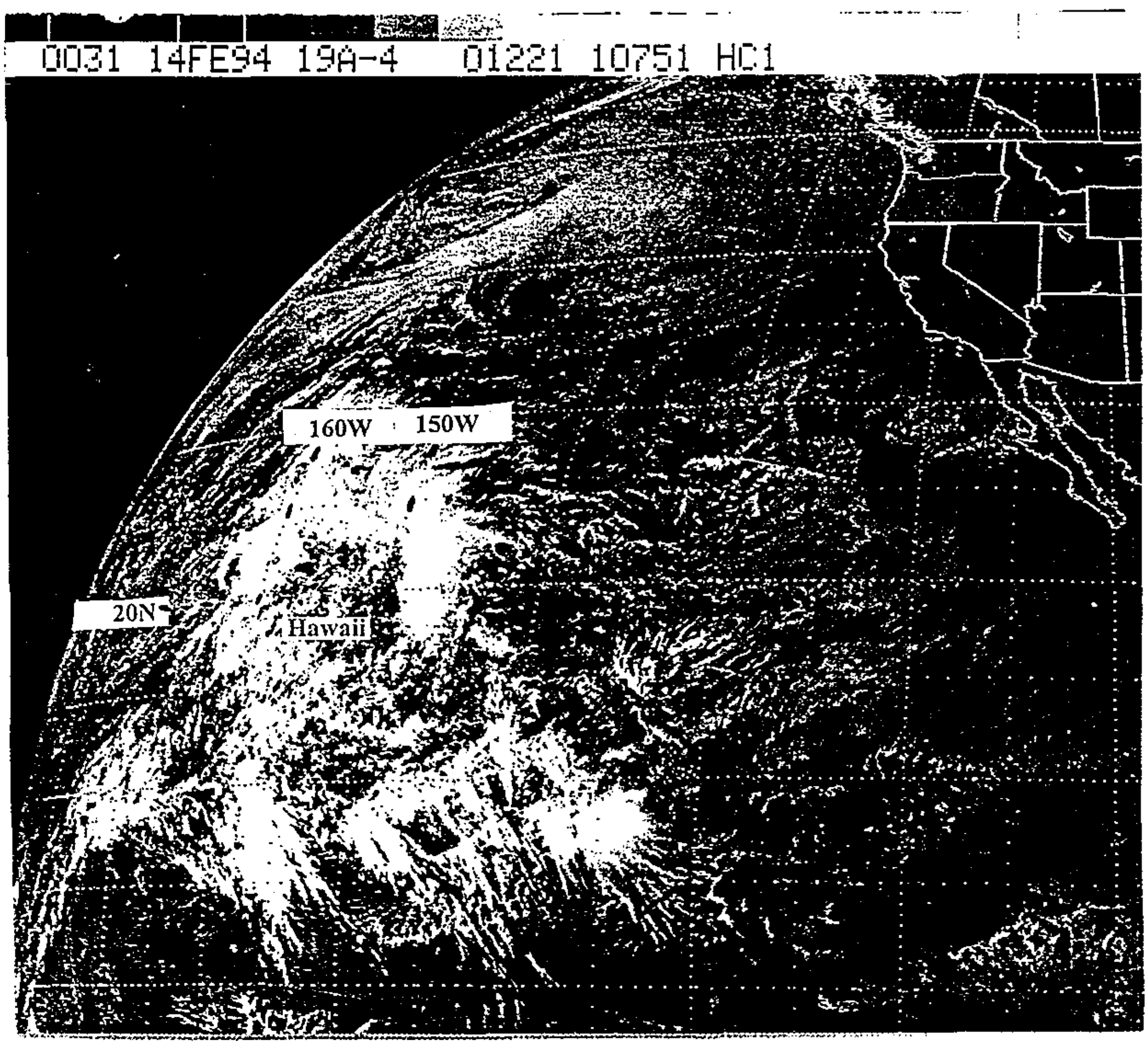


0031 UTC .... FEBRUARY 12, 1994

The satellite photographs are taken at 0031 UTC (2:31 pm Hawaii local time). Although extremely useful in the data sparse areas of the Pacific, satellite data does not provide forecasters with pinpoint accuracy in identifying specific areas of heavier rainfall, but does afford early signs of Kona storm development in the synoptic scale.

Figure 8 shows a typical signature of cloudiness associated with either an upper level low, or a surface based disturbance in the Pacific. Showers and embedded thunderstorms were west of Hawaii at this time. However, the presence of the synoptic scale trough with the accompanying jet was indicative of the potential for heavy rainfall.

FIGURE 9
GOES-7 SATELLITE PHOTOGRAPH



0031 UTC ... FEBRUARY 14, 1994

As seen in the upper level maps, the area between 150W and 160W was ripe for enhancement of activity as temperatures above 500-mb cooled significantly. Figure 9 shows the increase resulting from the destabilization which occurred.

As mentioned earlier, the WSR-88D was operating in a test mode and some data was retrieved. Besides using the base reflectivity data for identifying areas where heavy rainfall was occurring, the storm total precipitation (STP) product was examined and compared to ground truth rainfall observations.

Surface and radiosonde observations from Lihue, Kauai, and from Hilo, Hawaii provided verification for the wind data that was observed by the WSR-88D. The frequency of radar observations provided a more detailed chronology of the shift in the wind and its mesoscale relationship to the heavy rainfall event. For the Kona event, the base velocity data showed an excellent comparison to ground truth and upper air observations.

There was initial speculation that some of the WSR-88D's precipitation algorithms that had been developed would not provide outputs that would be representative for the tropics. With the Kona Low developing to maturity by February 14, 1994 at 0000 UTC (2 pm Sunday), steady rainfall commenced over the Hawaiian Islands and provided the WSFO with the opportunity to compare rainfall data.

Table 2 shows some of the heavier rainfall totals that were recorded at some of the LARC locations on Oahu. The totals in the table are provided for the period which correspond to the WSR-88D Storm Total Precipitation (STP) (**Figure 10**). The STP provides rainfall for the period from February 3 through 6 am Hawaii local time on February 14. Therefore, referring to the 15-minute rainfall records available at the WSFO, the column labeled Feb 12-14 incorporates rainfall through 6 am.

Table 2. Feb 3 (1:00 am) - Feb 14 (6:00 am) rainfall (in.)

Site #	Feb 3-11	Feb 12-14	TOTAL	WSR-88D	% Under/Overestimated
03	1.37	13.00	14.37	10.0	31% Underestimated
16	2.01	7.02	9.03	6.0	34% Underestimated
30	3.06	7.55	10.61	8.0	25% Underestimated
07	.22	6.39	6.61	5.0	24% Underestimated
09	.55	3.98	4.53	5.0	10% Overestimated
08	.29	2.11	2.40	3.0	25% Overestimated
25	1.77	3.84	5.61	3.0	47% Underestimated
05	.20	5.42	5.62	5.0	11% Underestimated

Note that the WSR-88D precipitation in this case provided anywhere from 24% to 34% below the actual recorded amounts over most sites, although an underestimate of 47% was noted for a gage near Diamond Head. The heavier rainfall was recorded over the Koolau range where orographic effects always play an important role in the development of precipitation. On the other hand, two leeward locations (both under 500 feet elevation) showed the radar indicating 10%-25% above the actual recorded amounts. Both locations represented rainfall totals of less than five inches.

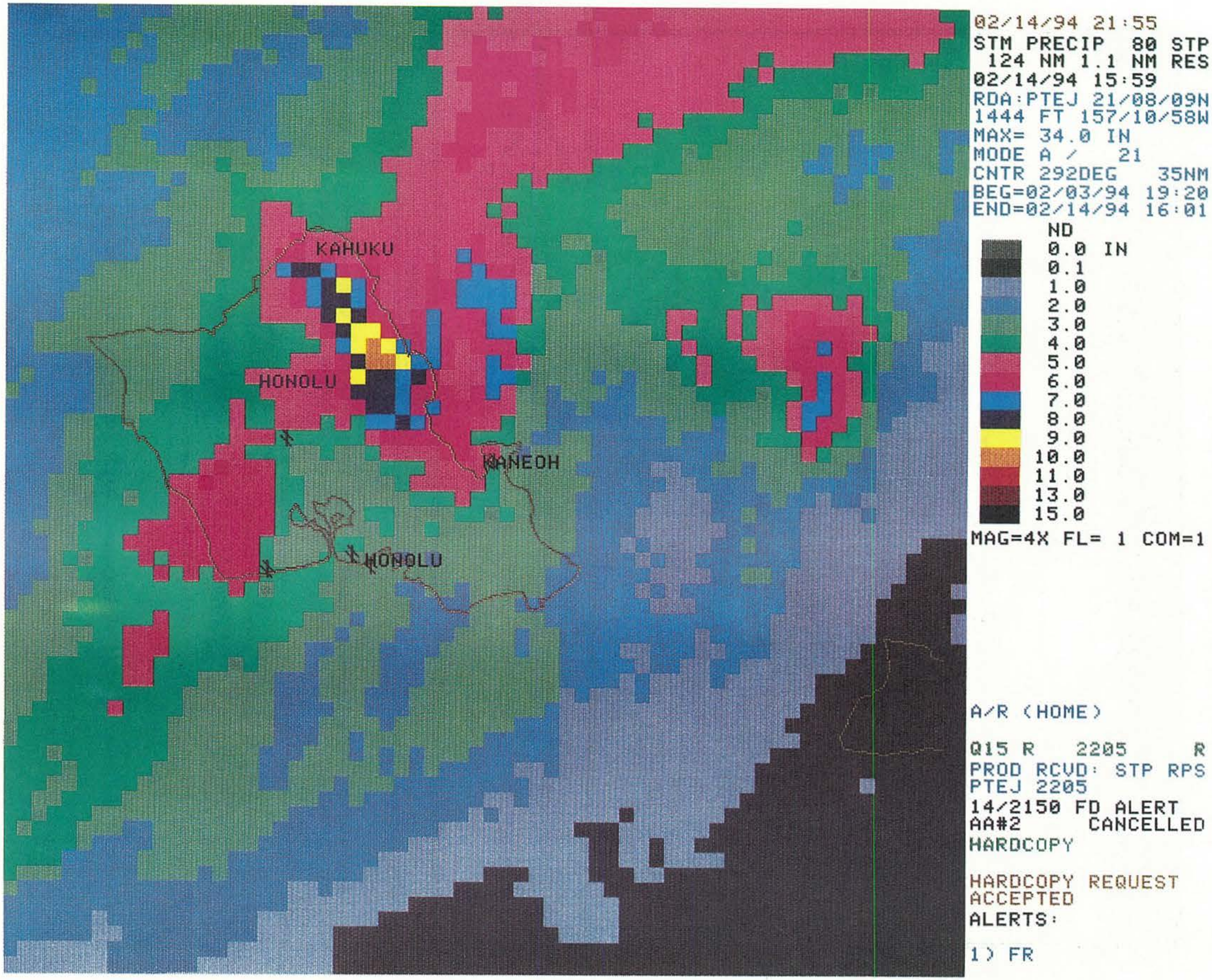


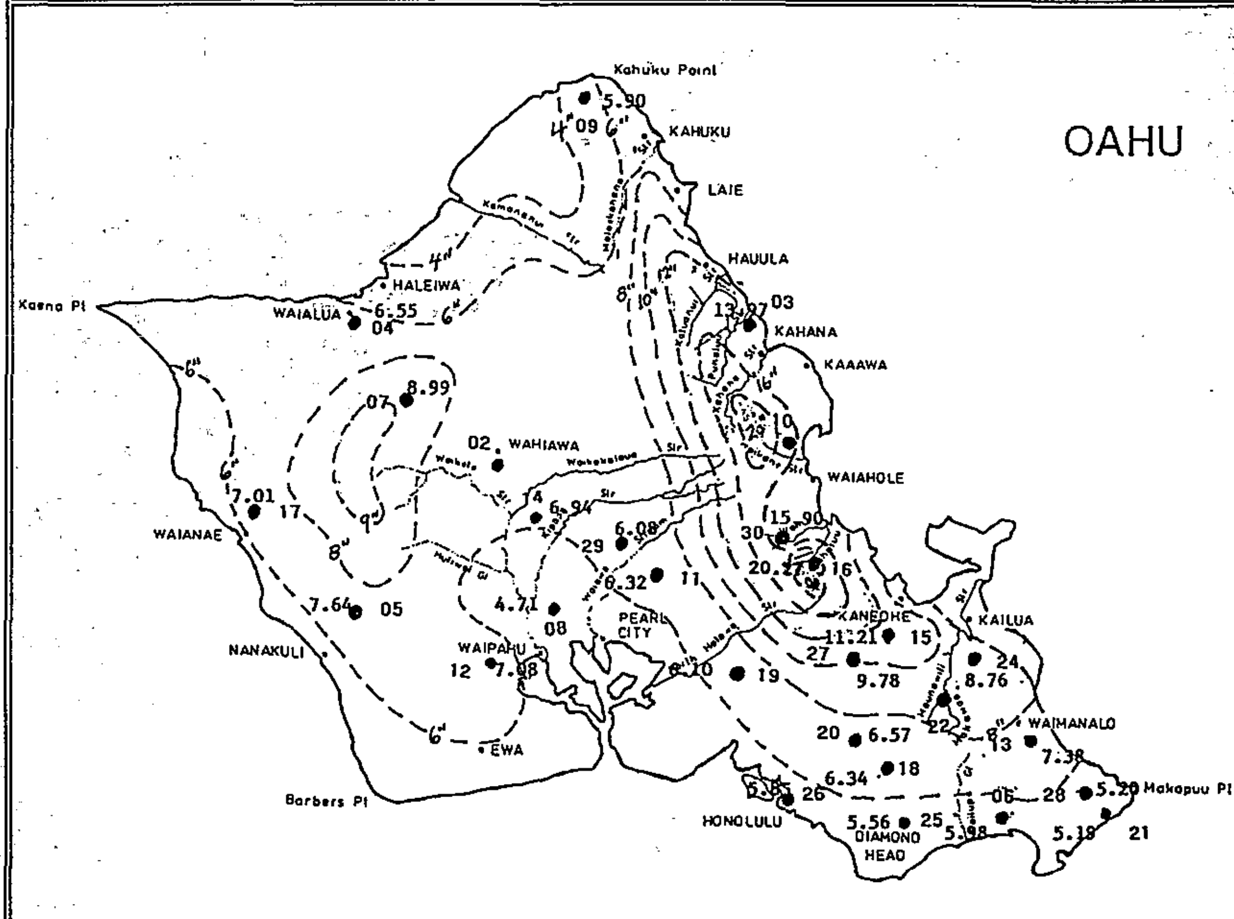
Figure 10

MOLOKAI, HI WSR-88D ..... Storm Precipitation Total (STP)

(Begin = 02/03/94 19:20Z End = 02/14/94 16:01Z)

Figure 11 provides an isohyet analysis of the February 12-17 Kona storm on Oahu.

FIGURE 11
FEBRUARY 12-17, 1994 - ISOHYET ANALYSIS



RAINFALL DATA FOR KONA STORM OVER OAHU

The Kona storm event produced most of the rainfall over Oahu between February 12-17, but heaviest daily totals occurred on February 13-14. The normally dry leeward sections received above 6 inches of rain with totals approaching nine inches over some sections of the Waianae Range.

Heavier rainfall amounts were recorded over the Koolau range where orographic effects always play an important role in the development of precipitation. For the six day period, over 15 inches of rain fell in the higher elevations west of the Waiahole-Hauula area, and the entire Koolau Range receiving over 8 inches of rain.

The main point to remember is that the leeward sections of Oahu will normally receive 6-9 inches of rain whenever a well developed Kona storm is identified. The addition of AWIPS type workstations, ASOS technology for almost continuous surface observations, and WSR-88D data will all help to identify the initiation and dissipation phases of significant Kona storms.

5. UPPER TROPOSPHERIC TROUGH

Another heavy rainfall producer that is typically responsible for flash flooding in Hawaii is the upper tropospheric trough that migrates into the region west of the islands and then drifts across the area.

Studies by Sadler (1967) indicate that strongest circulations exist near the 200-mb level and weaken downward. The existence of weak circulation supports a circulation that extends downward only to about 500-mb. Lyons (1992) stated that a moderate tropical upper tropospheric trough (TUTT) will usually display a slight eastward tilt from 200-mb down to the surface, usually becoming quasi-stationary for days at a time, during which time copious amounts of rain can be produced.

In the last two decades, tropical experts have identified an average of one to two cases per year where upper tropospheric troughs have adversely impacted weather conditions over the Hawaiian island chain. It is not uncommon to have rainfall totals approaching over 20 inches in a 24-hour period. Schroeder (1977) documented heavy rainfall occurrences where low level trades combine with orographic effects and synoptic scale forcing induced by the TUTT to produce excessive rainfall. Schroeder further recognized the need for a speed maximum immediately east of Hawaii, which he identified as the trigger that provides the generation of divergence aloft.

Cram and Tatum (1979) also addressed the different types of heavy rainfall producers over Hawaii. They identified upper level troughs and surface fronts as the main features responsible for producing heavy rainfall. In their studies, they determined that upper level troughs that stalled over or near the Hawaiian islands were often deep depressions that were centers of extremely heavy precipitation. It is important to note that in their studies, several of the heavy rainfall events occurred from warm clouds below the freezing level.

The second heavy rainfall event that occurred over Hawaii in 1994 can be traced to the dynamical interactions of a significant upper level trough and the low level easterly flow. For Oahu, this interaction resulted in several reports of 10-12 inch 24-hour rainfall totals on March 24, 1994. This was in addition to the 5-7 inch 24-hour totals that occurred over the same areas the previous day. For the March 22-25 event, the normally drier leeward sections received roughly between 4 and 7 inches of rain - higher elevations of the Koolau range received between 15-20 inches.

Landslides, power outages, flooding and traffic accidents were reported on Oahu. Debris-blocked streams and roads were flooded on Maui, Oahu, and the Big Island of Hawaii. Two fatalities occurred with this event in Maui as a family attempted to cross Kauaula stream near Lahaina in a jeep.

6. MARCH 22-25, 1994 EVENT - UPPER TROPOSPHERIC TROUGH

The surface analysis maps for this time period did not indicate any significant change in the low level trade wind flow over the area. The dominant low level feature was a strong quasi-stationary 1035-mb high pressure center which was located near 36N 150W on 1200 UTC, March 22nd. Although it had decreased to 1028-mb 36 hours later, it effectively blocked a weak cold front that was approaching the area from the northwest (near the dateline).

The 1000-500 mb thickness values were lower than those in the February 1994 case. However, no well-defined discontinuity in air masses was evident over Hawaii.

Figure 12 is the set of surface maps which correspond with the heavy rainfall event. In contrast to the February 1994 Kona storm event, the trigger for the precipitation was not evident in the low level flow. The March 1994 low level feature primarily contributing to the rainfall was the strong easterly flow which was advecting moisture that was lifted orographically in an area of instability afforded by the upper level trough.

The reflection of the upper level trough is seen on 1200 UTC, March 23rd at the surface. This was analyzed as a perturbation in the vicinity of the Hawaiian Islands. However, a closed circulation never did develop because the high pressure system maintained a strong pressure gradient, which produced strong trades of 20-35 knots below the 9 thousand foot level.

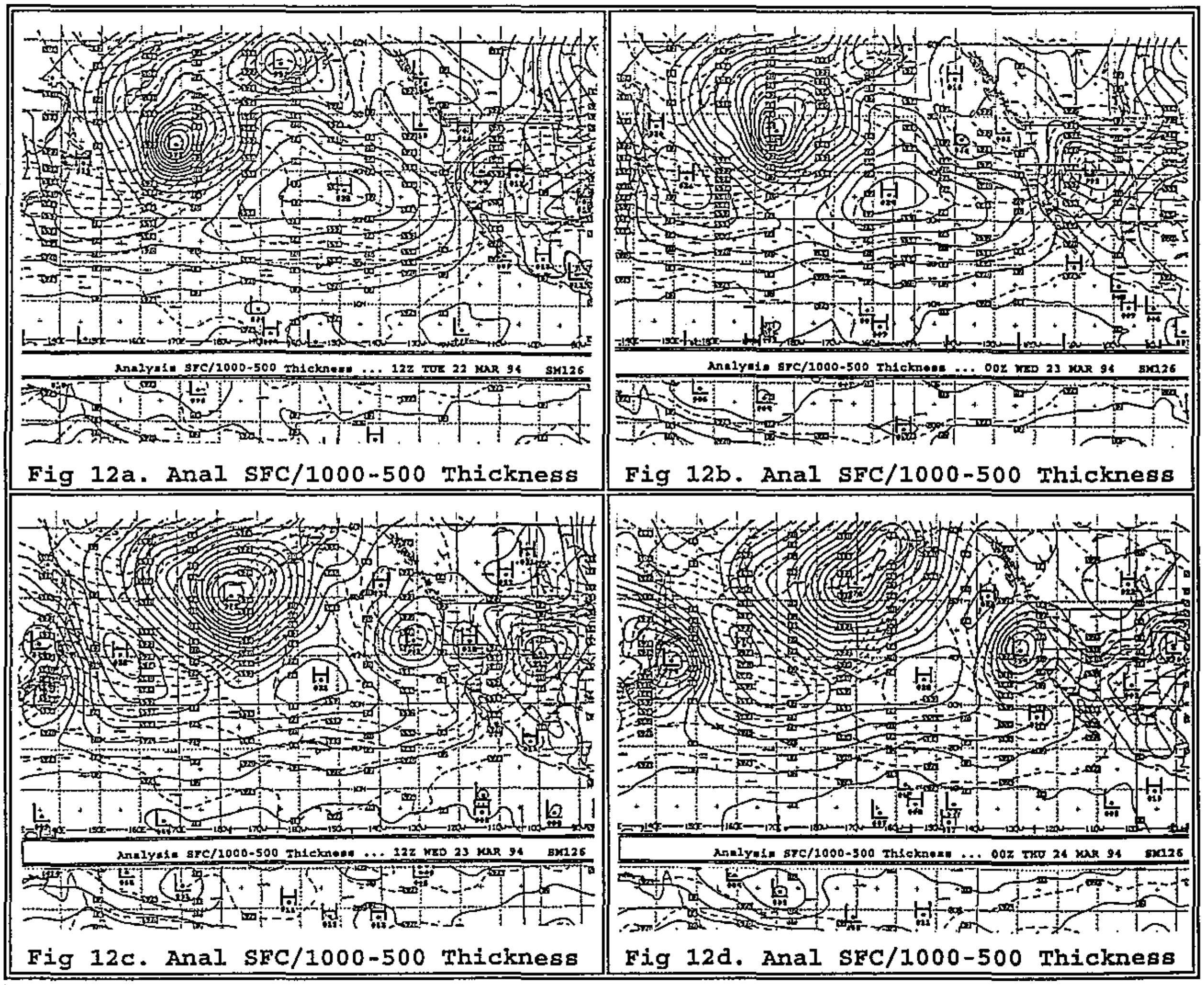


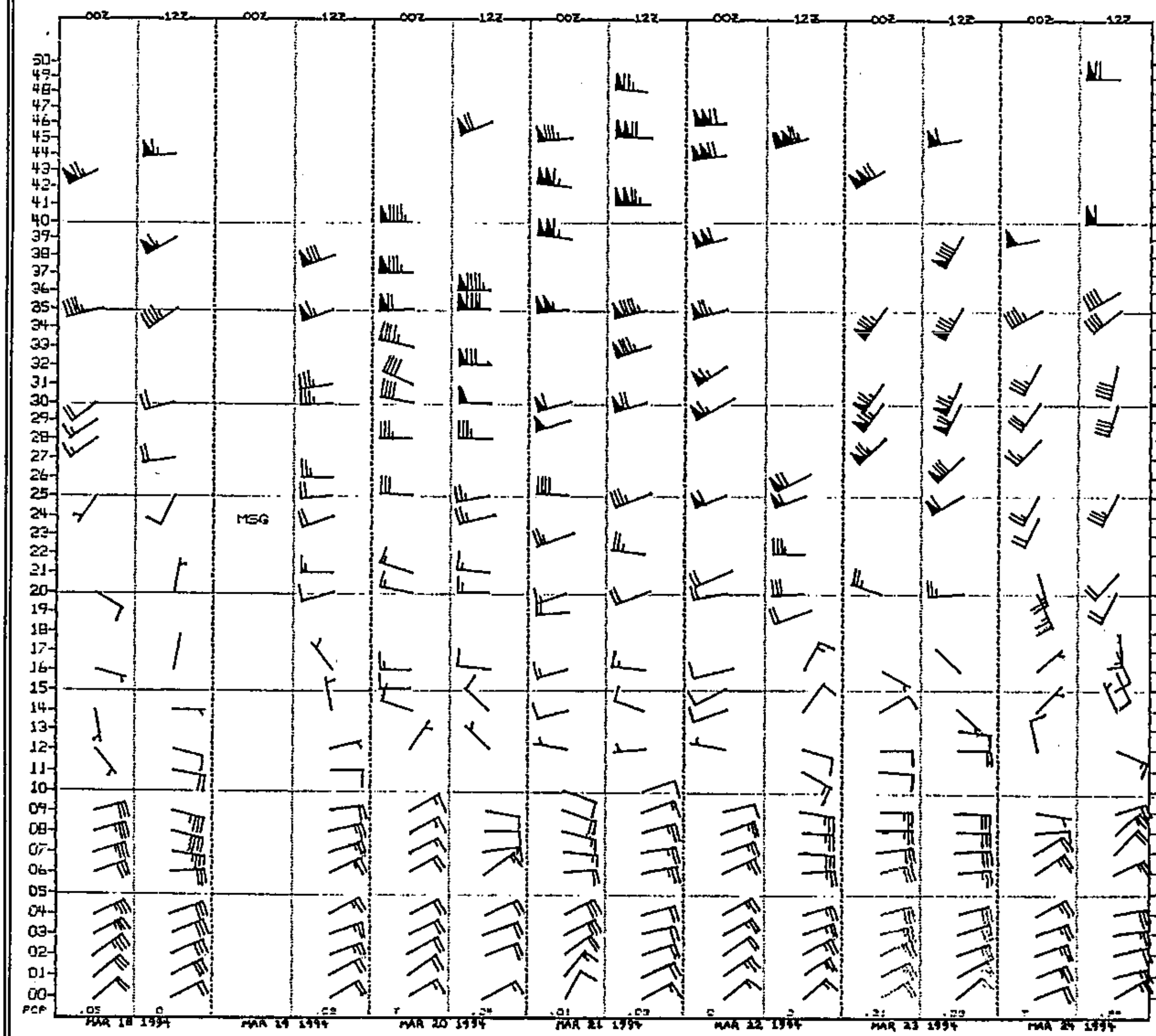
Fig 12a. Anal SFC/1000-500 Thickness **Fig 12b. Anal SFC/1000-500 Thickness**

Fig 12c. Anal SFC/1000-500 Thickness **Fig 12d. Anal SFC/1000-500 Thickness**

Figure 13 is a time section of the vertical wind profile for Lihue, Kauai, where the moderate to strong trades at the lower levels can be seen to continue throughout the entire period.

The Hilo, Hawaii vertical wind profile (not shown) did not contain the strong trade winds. Northeast and east winds in the lower 10 thousand feet were 10-15 knots throughout the entire period, perhaps resulting in less mesoscale precipitation than the northern islands received.

Figure 13
Lihue, Kauai time section plot



March 18-24, 1994

To reiterate, within the next few years, additional WSR-88D installations on Kauai and on the Big Island of Hawaii will provide a greater frequency in vertical wind profile data, which will be used extensively to help diagnose mesoscale features during heavy rainfall events.

Table 3 shows the daily rainfall totals as recorded by the LARC network throughout Hawaii for the March event. Rainfall records indicate that the first nineteen days of March 1994 were relatively dry, followed by a few days of normal precipitation and the heavy rainfall event. The greatest totals occurred on March 23-24, 1994.

Table 3
Rainfall data from 0100 to 0100 HST

March 1-31, 1994	[illegible]	[illegible]	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
KEY KAUAI																																	
48 ANAHOLA	3.18	12.64	.00	.00	.00	.00	.03	.00	.00	.00	.00	.09	.33	.02	.05	.18	.04	.01	.03	.00	.03	.23	.08	.02	.15	.49	.06	.31	.39	.02	.45	.91	.04
45 HANALEI	1.46	20.55	.00	.00	.00	.00	.00	.00	.00	.00	.00	.04	.31	.09	.13	.23	.02	.01	.00	.00	.01	.00	.00	.00	.00	.00	....	....	.18	.11	.08	.23	.02
49 HANAPEPE	1.19	7.32	.00	.00	.00	.07	.16	.00	.00	.00	.00	.00	.00	.00	.00	.01	.04	.00	.03	.00	.00	.02	.00	.17	.15	.56	.00	.00	.00	.00	.00	.00	.00
43 KALAHEO	2.98	12.94	.00	.01	.00	.12	.34	.00	.00	.01	.00	.00	.00	.03	.20	.22	.12	.05	.06	.01	.02	.11	.03	.78	.37	.46	.00	.03	.00	.01	.00	.00	.00
56 KAPAHI	2.58	24.04	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	.86	.26	.16	.55	.46	.29
46 KOKEE	4.23	12.54	.00	.00	.00	.05	.01	.00	.00	.00	.00	1.44	1.51	.05	.16	.16	.27	.10	.05	.00	.00	.04	.10	.09	.09	.26	.00	.00	.00	.00	.00	.00	.00
40 WAILUA	4.76	21.50	.00	.00	.00	.00	.05	.00	.00	.00	.00	.01	.01	.11	.28	.41	.24	.08	.04	.10	.02	.26	.00	.14	.48	1.06	.23	.34	.22	.14	.03	.05	.19
41 [illegible]	9.27	28.77	.00	.00	.00	.00	.00	.00	.00	.00	.00	.34	1.53	.12	.27	.50	.43	.07	.14	.04	.01	1.08	.11	1.38	.25	1.06	.04	.38	.31	.06	.00	.35	.00
OAHU																																	
18 AHUIMANU LOOP	11.99	35.16	.00	.00	.00	.08	.47	.00	.00	.00	.00	.11	.12	.00	.06	.27	.06	.01	.00	.00	.16	.37	.16	.09	3.99	8.37	.42	.35	.25	1.09	.34	.25	.03
26 ALOHA TOWER	5.75	13.18	.00	.00	.00	.03	.43	.00	.00	.00	.00	.00	.02	.00	.01	.14	.12	.12	.09	.00	.01	.13	.03	.04	.78	3.61	.28	.00	.00	.00	.00	.00	.00
10 KAIPUU KAUKA	11.97	21.99	.00	.00	.00	.05	.13	.00	.00	.00	.00	.01	.41	.00	.03	.66	.02	.03	.02	.01	.01	.21	.09	.06	2.41	5.39	.20	.17	.14	.23	1.36	.47	.00
21 HAWAII KAI	4.83	12.60	.00	.00	.00	.00	.19	.00	.00	.00	.00	.00	.24	.00	.00	.00	.04	.03	.00	.01	.01	.03	.00	.00	1.45	2.51	.11	.02	.00	.00	.00	.00	.00
09 KAHUKU	3.26	12.30	.00	.00	.00	.00	.05	.00	.00	.00	....	.00	.19	.00	.04	.03	.03	.02	.02	.00	.00	.31	.01	.04	.28	1.87	.08	.03	.00	.05	.21	.00	.00
26 KAKEHAKE	5.17	14.42	.00	.00	.00	.00	.74	.00	.00	.00	.02	.00	.35	.00	.00	.02	.02	.00	.01	.05	.00	.04	.01	.00	1.23	2.42	.00	.15	.00	.00	.02	.00	.00
12 KUNIA SUBSTN	.70	9.21	.00	.00	.00	.17	.20	.00	.00	.00	.00	.00	.06	.00	.00	.00	.00	.01	.00	.00	.00	.26	.00	....	....	....	....	....	.00	.00	.00	.00	.00
05 LUALUALEI	4.70	13.60	.00	.00	.00	.16	.56	.00	.00	.00	.00	.00	.07	.00	.00	.00	.00	.01	.00	.00	.01	.03	.04	.01	.85	2.87	.06	.00	.00	.03	.00	.00	.00
15 LULUKU	15.19	38.90	.00	.00	.00	.00	.64	.00	.00	.00	.01	.03	.24	.00	.11	.13	.14	.04	.03	.05	.00	.55	.04	.21	3.56	7.33	.56	.29	.07	.64	.09	.26	.00
18 MANOA LYON ARBO	28.02	54.06	.00	.00	.00	.01	.76	.01	.00	.00	.32	.10	.17	.02	.18	.29	.20	.19	.09	.37	.15	1.07	.22	.59	7.15	12.74	1.19	.29	.45	.65	.09	.00	.01
22 MAUNAWILI	18.99	43.84	.02	.00	.02	.02	.68	.00	.00	.02	.00	.02	.33	.01	.07	.11	.05	.03	.06	.11	.04	.75	.04	.10	5.00	9.77	.44	.07	.21	.37	.03	.20	.02
14 MILILANI	7.54	16.75	.00	.00	.00	.03	.28	.00	.00	.00	.00	.00	.19	.00	.00	.03	.10	.07	.01	.00	.01	.18	.01	.15	1.78	4.73	.14	.03	.00	.05	.12	.00	.05
19 MOANALUA	12.37	24.32	.00	.00	.00	.12	.30	.00	.00	.00	.01	.00	.05	.00	.01	.13	.17	.07	.04	.00	.07	.78	.42	.50	2.65	5.72	.30	.10	.09	.05	.01	.00	.00
06 NIU VALLEY	11.46	24.17	.00	.00	.00	.02	.58	.01	.00	.00	.00	.00	.25	.05	.03	.10	.09	.13	.04	.10	.00	.15	.04	.00	2.73	5.76	1.00	.16	.22	.00	.00	.00	.00
20 NUUANU WATERSUP	23.12	48.04	.00	.00	.00	.01	.75	.00	.00	.00	.11	.07	.29	.07	.10	.22	.28	.15	.06	.09	.11	1.14	.10	.49	5.13	11.62	1.32	.28	.25	.52	.04	.01	.00
24 OLOMANA	8.73	25.14	.00	.00	.00	.00	.20	.00	.00	.02	.00	.01	.23	.00	.04	.09	.05	.05	.00	.01	.02	.27	.01	.05	2.11	4.54	.21	.02	.04	.05	.30	.01	.00
11 PALISADES	10.23	22.13	.00	.00	.00	.03	.20	.00	.00	.00	.00	.00	.16	.00	.02	.15	.23	.08	.01	.01	.08	.44	.27	.65	2.37	4.81	.35	.10	.08	.15	.00	.00	.00
25 PALOLO F.S.	11.35	25.88	.00	.00	.00	.02	.64	.00	.00	.03	.00	.00	.02	.00	.02	.07	.18	.07	.03	.06	.04	.47	.18	.11	2.21	8.68	.89	.06	.11	.04	.00	.00	.00
07 POAMOHO	8.91	18.85	.00	.00	.00	.00	.11	.00	.00	.00	.00	.00	1.29	.00	.00	.02	.05	.03	.00	.00	.06	.17	.00	.05	.72	4.84	.22	.06	.02	.04	.03	.01	.00
03 PUNALUU PUMP	9.85	33.55	.00	.00	.00	.08	.68	.00	.00	.00	.00	.17	.82	.00	.02	.11	.07	.02	.00	.03	.00	.12	.09	.12	1.76	4.77	.15	.19	.04	.12	1.21	.17	.00
04 WAIALUA	5.06	13.54	.00	.00	.00	.00	.01	.00	.00	.00	.00	.00	.28	.00	.00	.01	.00	.01	.00	.00	.02	.13	.01	.08	.57	3.77	.10	.04	.02	.00	.01	.00	.00
17 WAIANAE KAWIWI	4.31	12.25	.00	.00	.00	.11	.49	.00	.00	.00	.00	.00	.11	.00	.00	.00	.01	.00	.00	.00	.00	.00	.00	.00	.41	3.09	.09	.00	.00	.00	.08	.00	.00
29 WAIAWA	10.11	20.50	.00	.00	.00	.02	.48	.00	.00	.00	.00	.00	.16	.00	.03	.14	.19	.07	.05	.00	.12	.58	.10	.37	2.24	4.97	.29	.10	.03	.12	.01	.00	.00
30 WAIHEE PUMP	18.74	46.78	.01	.00	.00	.08	.46	.00	.00	.00	.01	.29	.12	.01	.04	.14	.11	.01	.00	.02	.09	.21	.16	.11	3.63	8.54	.24	.32	.27	1.04	.42	.43	.02
13 WAIMANALO	7.20-	19.89	.00	.00	.00	.00	.43	.00	.00	.02	.00	.00	.32	.00	.03	.01	.04	.00	.02	.04	.00	.19	.00	.01	2.09	3.44	.20	.01	.12	.00	.02	.01	.00
08 WAIPIO	5.43	11.67	.00	.00	.00	.18	.30	.00	.00	.00	.00	.00	.10	.00	.00	.01	.11	.05	.01	.00	.01	.09	.00	.05	1.37	3.33	.02	.00	.00	.00	.00	.00	.00
02 WHEELER AFS	7.27	11.63	.00	.00	....	....	.11	.01	....	.00	.00	.00	.34	.00	.00	.02	....	.18	.04	.00	.11	.29	.04	.32	1.32	4.13	.14	.02	.00	.07	.09	.00	.04
27 WILSON TUNNEL	20.80	48.55	.00	.00	.00	.00	.75	.01	.00	.00	.01	.02	.35	.01	.17	.17	.18	.09	.03	.07	.02	.86	.07	.29	4.53	10.30	.78	.31	.15	1.26	.06	.25	.07
MOLOKAI																																	
71 KAUNAKAKAI [illegible]	1.38	5.34	.00	.00	.00	.00	.00	.00	.00	.01	.00	.00	.12	.00	.00	.01	.00	.00	.00	.00	.00	.00	.00	.00	.83	.35	.00	.00	.00	.00	.00	.00	.00
73 KONOLO	5.15	10.21	.01	.00	.00	.00	.00	.01	.01	.02	.01	.01	.00	.00	.01	.05	.09	.03	.00	.01	.08	.06	.00	.29	2.54	1.85	.03	.06	.00	.00	.02	.02	.01
LANAI																																	
72 LANAI CITY	3.43	10.72	.00	.00	.00	.00	.11	.05	.00	.00	.04	.00	.19	.00	.01	.02	.01	.00	.00	.00	.00	.05	.00	.00	2.05	.21	.22	.00	.19	.24	.01	.01	.00
MAUI																																	
69 HAIKU	17.59	18.76	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.75	.68	....	....	....	....	....	....	.33	.46	.68	1.94	5.50	5.79	.31	.01	.71	.25	.22	.00	.00
61 HANA	25.61	49.13	.00	.00	.00	.30	.00	.00	.00	.00	.00	.00	1.73	.84	.01	.29	.07	.19	.05	.09	.05	.46	.01	.79	8.10	12.01	.52	.16	1.06	.63	.01	.00	.00
74 KAHAKULOA	.00	.02	....	....	.00	.00	.00	.00	.00	.00	.00	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	.00	....	....
75 KIHEI-2	1.30	4.07	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.04	.01	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.32	.91	.02	.00	.00	.00	.00	.00	.00
85 KULA	2.13	4.21	.00	.00	.00	.00	.00	.00	.00	.00	.00	.04	.17	.04	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.70	1.81	.04	.00	.00	.00	.00	.00	.01
62 MAHINAHINA	13.57	21.39	.00	.00	.00	.00	.02	.00	.00	.00	.00	.00	1.13	.75	.11	.51	.16	.25	.06	.02	.27	.44	.13	1.20	4.12	2.44	1.22	.10	.35	.05	.00	.00	.00
70 PUKALANI	11.40	18.63	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	1.17	.67	.34	.44	.29	.27	.06	.03	.00	.06	.04	.21	5.34	4.84	1.12	.18	.30	.04	.00	.00	.00
84 ULUPALAKUA	.88	5.55	.00	.00	.00	.00	.00	.01	.00	.00	.00	.00	.04	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.01	.41	.17	.08	.05	.02	.03	.03	.01	.02
78 WAIKAPU CC	5.64	11.55	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.28	.38	.07	.14	.01	.03	.02	.00	.01	.00	.00	.05	1.03	1.35	1.40	.01	.85	.07	.00	.00	.00
66 WAILUKU	7.11	12.83	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.56	.42	.08	.28	.06	.03	.05	.02	.02	.01	.00	.29	1.68	3.78	.56	.00	1.00	.25	.00	.01	.00
HAWAII																																	
94 GLENWOOD	22.89	55.78	.00	.00	.00	.00	.00	.06	.00	.02	.54	.04	.30	1.79	1.10	1.24	1.82	.90	.52	.68	.85	1.82	1.93	2.22	1.98	2.21	.78	.41	.15	.45	.09	.44	.53
35 HONAUNAU-2	4.38	8.55	.31	.66	.00	.00	.00	.10	.00	.00	.05	.00	.00	.00	.04	.00	.10	.00	.00	.00	.00	.00	.30	1.10	.29	.38	.01	.00	.05	.01	.00	.00	.18
87 HONOKAA	20.52	43.71	.00	.00	.00	.00	.00	.00	.00	.00	....	.01	1.28	4.55	.95	1.02	.74	.48	.37	.79	1.44	.91	1.50	.31	1.52	1.18	2.02	.74	.02	.19	.00	.12	.02
96 KAHUA RANCH	13.73	24.69	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	1.95	2.60	.74	.73	.75	.28	.29	.29	.22	.09	.46	.21	.64	.42	3.12	.12	.00	.00	.00	.00	.00
90 KAHAKOA	1.78	5.33	.00	.00	.00	.00	.00	.00	.00	.00	.00	.15	.01	.07	.02	.00	.00	.00	.00	.00	.00	.00	.00	.10	.22	.44	.75	.00	.00	.00	.00	.00	.00
86 KAMUELA	16.70	25.05	.00	.00	.01	.00	.00	.00	.06	.01	.00	.00	1.86	2.60	1.45	1.15	1.16	.20	.27	.49	.27	.28	.34	.18	.64	.70	4.51	.40	.00	.11	.00	.01	.00
97 KAMUELA UPPER	21.05	34.10	.00	.00	.00	.00	.00	.00	.00	.04	.00	.00	.83	3.07	3.07	2.78	1.68	.25	.53	1.19	.58	.57	.91	.21	1.17	.93	2.38	.23	.00	.09	.00	.00	.00
64 KEALAKEKUA	3.13	6.13	.00	.49	.15	.00	.00	.00	.00	.18	.08	.59	.00	.00	.00	.00	.22	.00	.00	.02	.01	.04	.24	.36	.23	.31	.05	.00	.02	.12	.01	.00	.03
80 LAUPAHOEHOE	21.39	57.71	.00	.00	.00	.14	.36	.01	.00	.00	.03	.00	.08	1.93	.04	.65	.30	.44	.18	.43	.02	1.06	.82	1.38	3.05	5.80	2.14	.74	.31	1.05	.00	.28	.39
81 MOUNTAIN VIEW	17.55	44.35	.00	.00	.00	.00	.00	.00	.00	.01	.07	.02	.32	2.21	.30	.49	.86	.65	.28	.82	.55	1.19	1.47	2.00	2.06	2.78	1.29	.20	.22	.00	.00	.00	.00
65 PAHALA	6.92	16.50	.45	.00	.00	.00	.55	.31	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.02	.25	.70	.57	3.34	.00	.00	.04	.02	.01	.58	.06
43 PAHOA	13.89	52.02	.00	.00	.00	.15	.24	.00	.00	.01	.02	.03	.01	.21	.11	.23	.31	.30	.05	.40	.11	.27	.41	2.70	2.57	4.54	....	....	.19	.54	.01	.35	.13
91 PIIHONUA	29.04	60.53	.00	.00	.00	.00	.00	.00	.00	.00	.14	.11	.55	1.90	.68	.92	.80	.74	.52	.58	.77	1.33	1.01	2.28	2.35	8.15	2.82	.16	.05	.00	.03	1.58	1.71
88 UPOLU AIRPORT	.33	4.60	....	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.01	.00	....	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.12	.00	.18	.02	.00	.00	.00
82 WAIAKA	2.11	5.98	.00	.05	.18	.00	.00	.00	.00	.03	.11	.28	.00	.00	.00	.00	.05	.00	.00	.00	.13	.00	.14	.53	.03	.33	.01	.00	.00	.03	.00	.00	.23
52 WAIAKEA UKA	23.87	80.85	.00	.00	.00	.00	.00	.00	.00	.02	.14	.04	.53	2.51	.84	1.04	1.01	.48	.85	.72	.54	1.25	.00	1.33	2.47	5.27	2.27	.27	.08	.57	.01	.74	1.83
MAX 24 HOUR VALUE =			.45	.66	.16	.30	.88	.31	.41	.18	.54	1.44	1.95	4.55	3.07	2.78	1.86	.90	.85	1.19	1.44	1.93	1.93	2.70	7.15	12.74	4.51	.38	1.04	1.24	1.38	1.58	1.71

March 1994

The 24-hour rainfall totals indicate that the March upper tropospheric trough did not affect all of Hawaii as the February Kona Storm did. In this case, heavier 24-hour totals were found mainly over Oahu where the Manoa Lyon Arboretum gage recorded 7.15 inches on March 23rd and 12.74 inches on March 24th.
The island of Kauai did not receive any significant rainfall, while Molokai and Lanai only received less than 3 inches. Maui and the Big Island had a few recorded amounts over 5 inches but, on the whole, the rainfall was below 3 inches for the same two day period.

At 700-mb, **Figures 14a-d**, a tight surface pressure gradient was noted to the south of Hawaii at 1200 UTC on Tuesday, March 22, 1994, with a well defined inverted trough nosing northeast over Johnston Island.

Twenty-four hours later, a cyclonic circulation began to form near 17N 166W and a significant moisture influx at 10,000 feet occurred over Lihue, Kauai as indicated by complete saturation at that level.

By 0000 UTC on Thursday, March 24, 1994, the cyclonic circulation had become closed just to the southwest of the Hawaiian Islands.

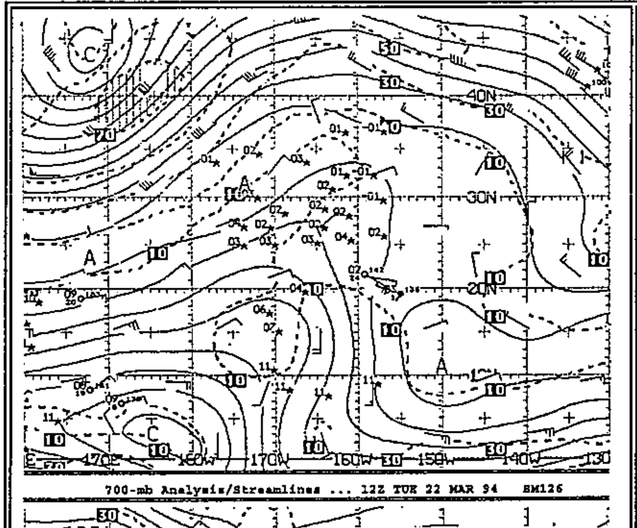


Figure 14a

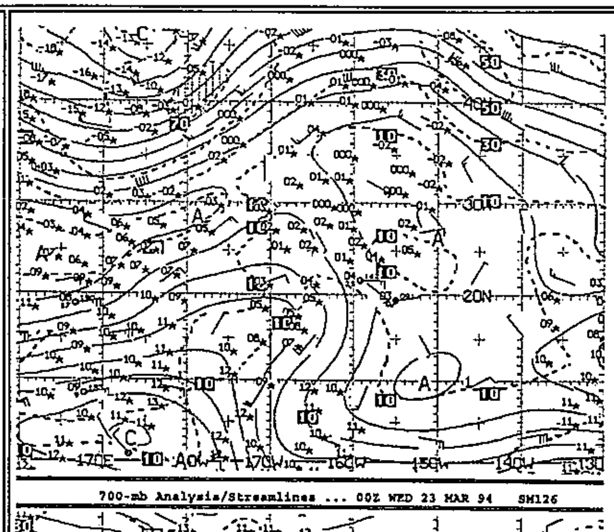


Figure 14b

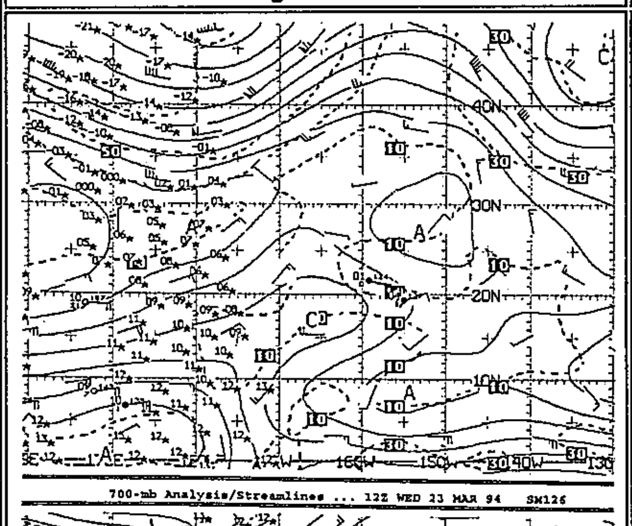


Figure 14c

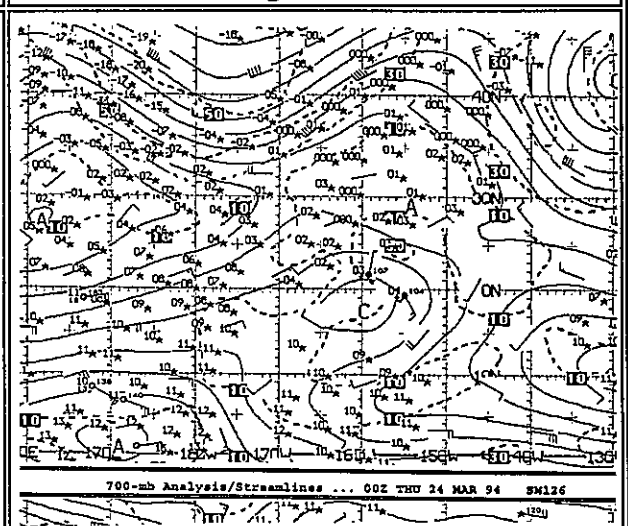


Figure 14d

Winds at 700-mb at Lihue were south to southeast at 5-15 knots throughout the first 36 hours. These winds increased in response to the development of the cyclonic circulation and the tightening of the pressure gradient southeast of Hilo, Hawaii. Temperatures remained fairly constant during the 48-hour period when the heavy rainfall occurred, ranging from 1 to 4 degrees Celsius over Lihue and Hilo.

Although no vertical motion fields were calculated for this event, it has been previously shown (Kiladis and Weickmann, 1991) that there is strong upward motion ahead of the trough axis. The strongest ascent is found near 20N although the trough induces upward motion as far south as the equator. Subsidence, on the other hand, usually peaks as the anticyclone at the jet exit region reaches its maximum amplitude. The ascent is consistent with the upper-level advection of positive vorticity in the quasigeostrophic sense. In the future, advanced workstations running gridpoint diagnostics will be able to provide isentropic potential vorticity (IPV) values. Then the diagnostic interpretations can be used to identify areas of vortex stretching and decreasing static stability.

Figures 15a-d show the 500-mb trough remaining west of Hawaii through 36 hours. One can assume that omega (vertical motion) would therefore be greatest ahead of the trough and therefore produce a significantly large precipitation area. Figure 15d shows that the 500-mb trough moves very close to Hawaii. At this time, the cyclonic vorticity advection is the greatest, and provides the strongest forcing for production of precipitation. This is verified by the amount of rainfall that occurred (see Table 3) on March 23-24, 1994.

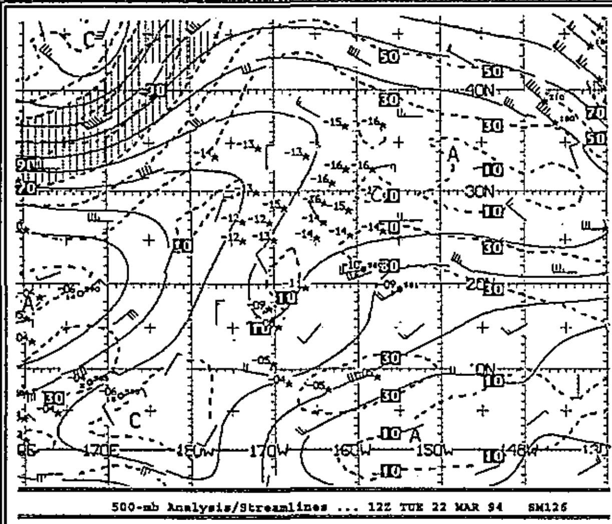


Figure 15a

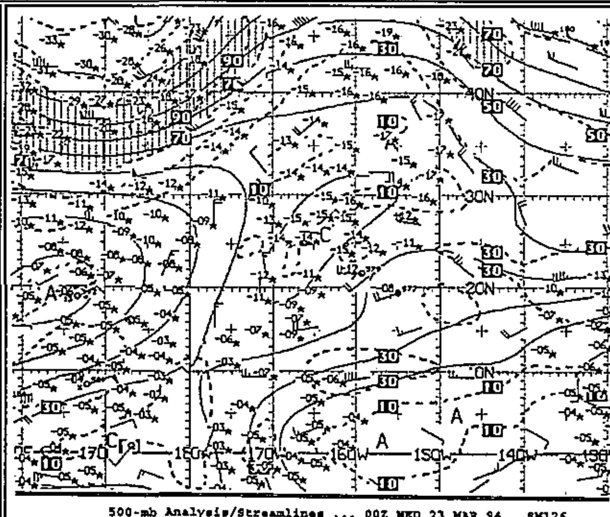


Figure 15b

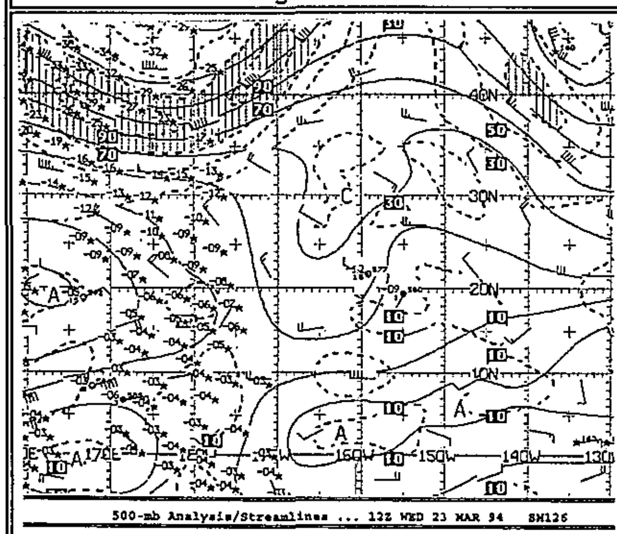


Figure 15c

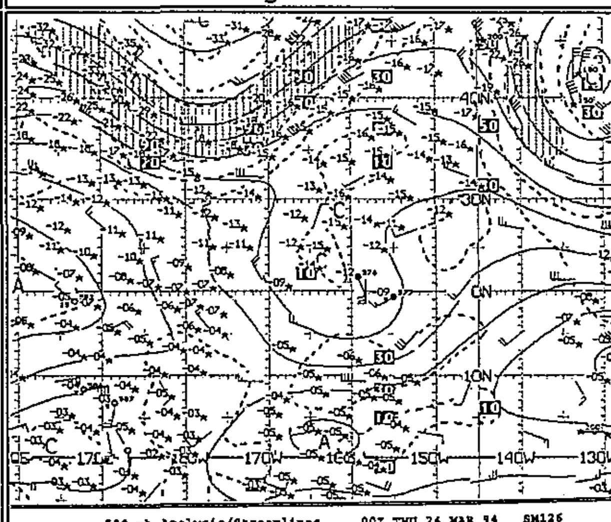


Figure 15d

The WSR-88D at Molokai was intermittently operational during this time period. On the whole, the data was very similar to the earlier case, with the exception being the Velocity Azimuth Display (VAD) Wind Profile (VWP) product which maintained its trade wind flow throughout the period. Winds were generally northeast and east 15-25 knots.

On March 23, 1994, at 0213 UTC, the Molokai WSR-88D base reflectivity data for the 0.5 degree elevation angle indicated a large precipitation area moving into radar range over the Pacific waters to the south of Hawaii. Destabilization had occurred as the upper level trough became established and pockets of cooler air at upper levels dropped deep into the tropics. The reflectivity values of the storms moving toward Hawaii were 25-30 dBZ.

By March 24, 1994, at 1432 UTC (**Figure 16**), the WSR-88D 248 nautical mile data of base reflectivity at 0.5 degree elevation angle was indicating reflectivity values of 25-30 dBZ oriented north to south through Oahu and the Kauai Channel. Large areas of embedded 35-45 dBZ were occurring over the Koolau Range and also 75-100 miles due south of Oahu. All of the showers and embedded thunderstorms were moving north at 20-25 knots.

Throughout the upper tropospheric trough event, several mesocyclone signatures were observed. All were very short-lived and no significant rotation was ever detected.

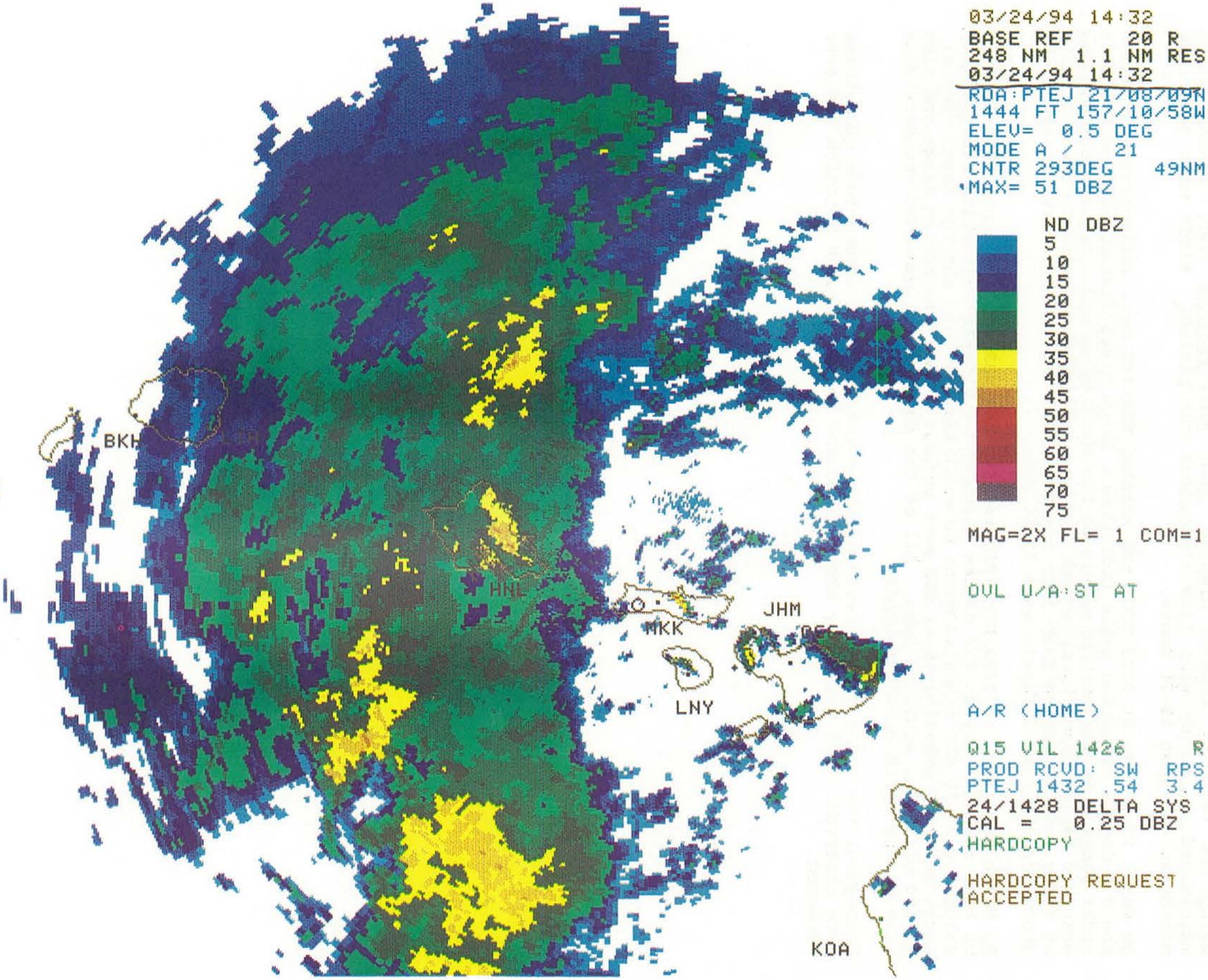


Figure 16
MOLOKAI, HI WSR-88D ..... Base Reflectivity (R)
(03/24/1994 - 1432Z)

At 250-mb, Figures 17a-d show the right entrance region of the jet stream impacting the weather over Hawaii as the jet streak approaches the ridge crest. This results in the creation of significant upward vertical motion. There is a definite similarity in the upper level conditions which triggered heavy rainfall during the February and March cases.

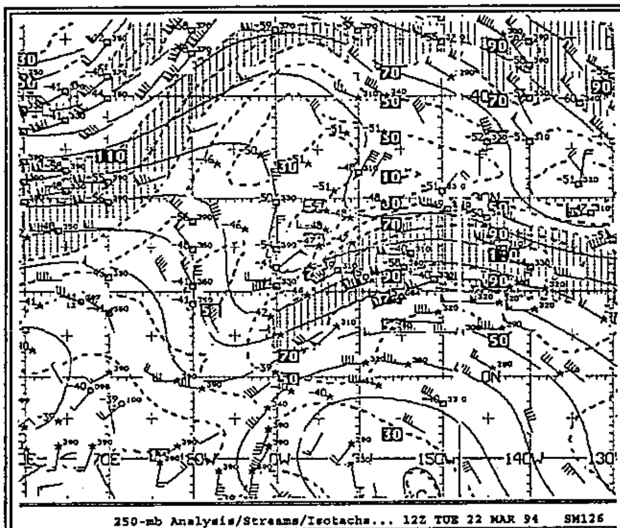


Figure 17a

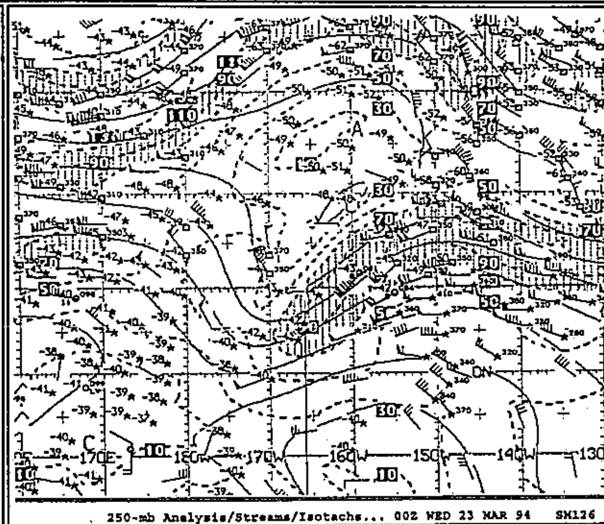


Figure 17b

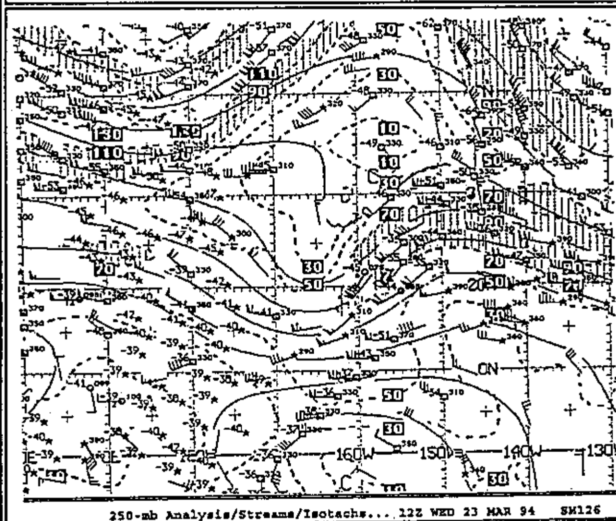


Figure 17c

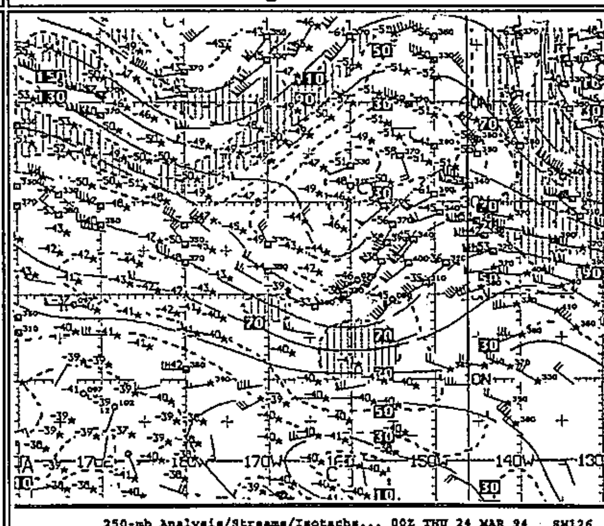
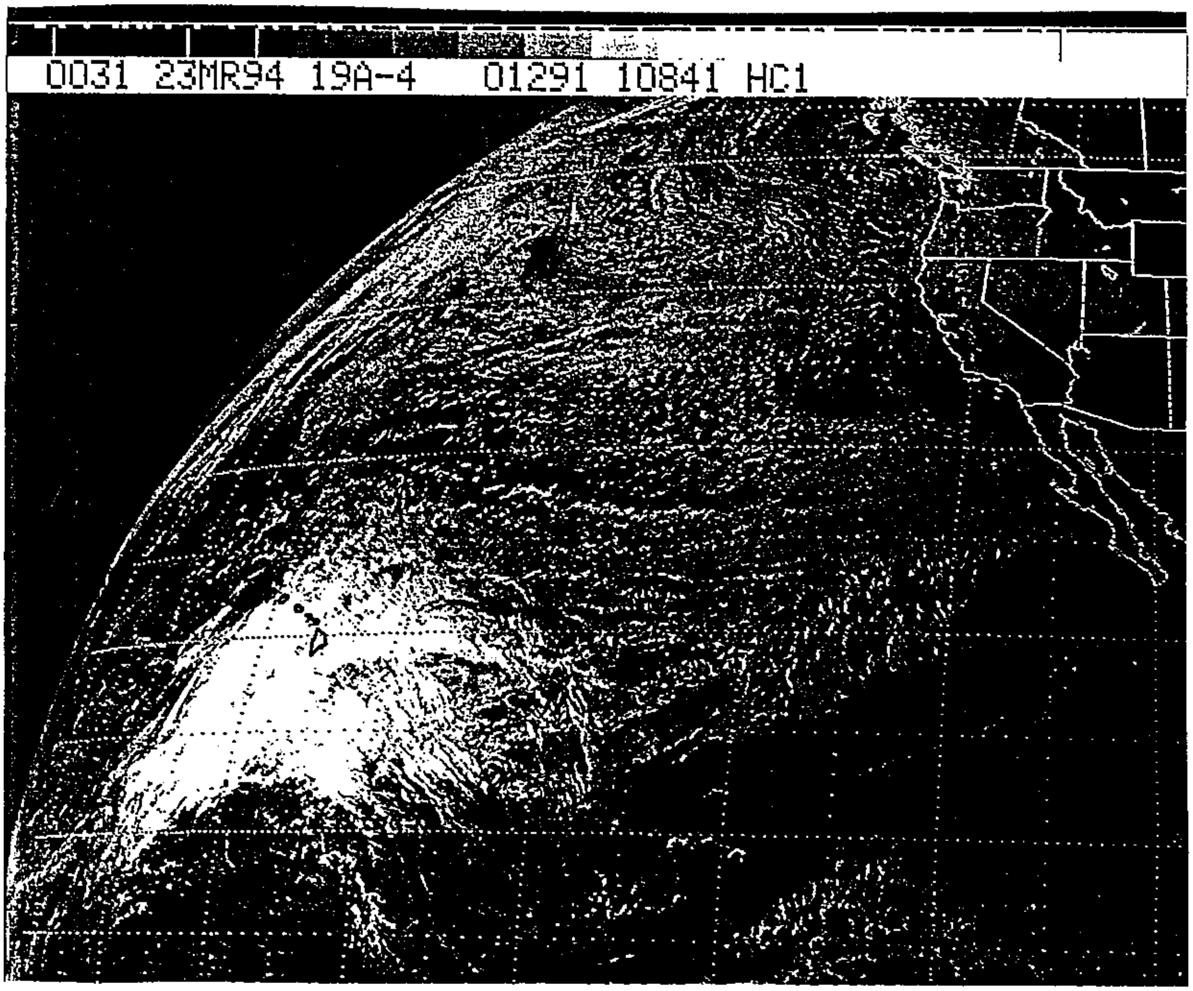


Figure 17d

Two satellite photographs (Figures 18 and 19) show the enhanced area of cloudiness to the south and west of Hawaii on March 23, 1994 at 0031 UTC. This gives an indication of the northeast movement during the following 24 hours. As with the February heavy rainfall situation, satellite photographs were helpful in locating the synoptic scale cloudiness and signatures of embedded precipitation. In order to pinpoint the exact locations of the heavy rainfall pockets, the forecaster is required to use the WSR-88D data when the precipitation is within the 250 nautical mile radius of the radar.

Figure 18
GOES-7 SATELLITE PHOTOGRAPH

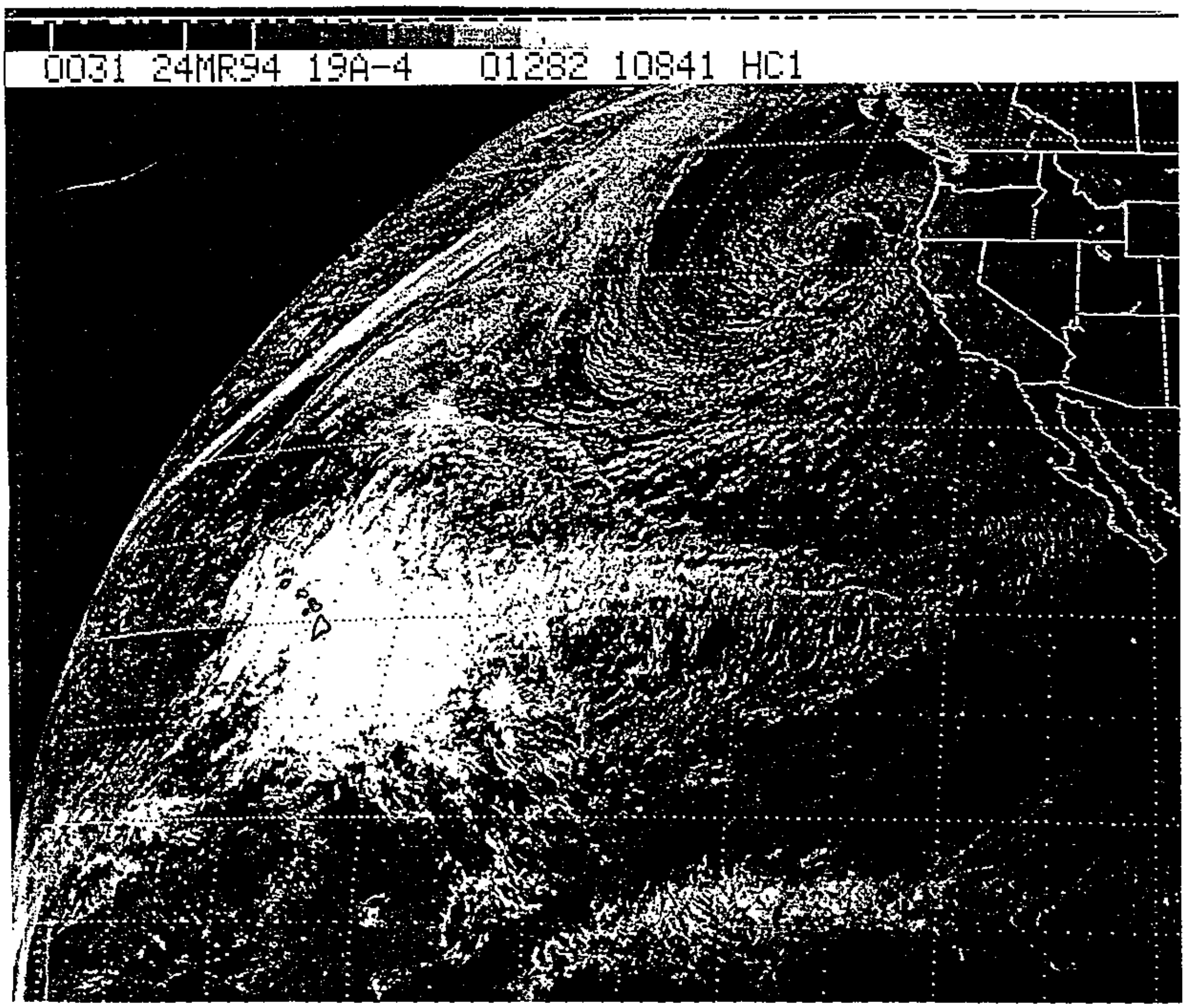


0031 UTC ... MARCH 23, 1994

WSR-88D data during this period indicates that rainfall was mainly occurring over sections of the Big Island of Hawaii and over windward sections, as well as over some of the higher elevations of Maui and Oahu. Elsewhere, no rain was occurring and only cloudy conditions were observed.

Figure 19 shows the location of the cloud mass over Hawaii twenty-four hours later when the WSR-88D was showing a band of rainfall between the Kauai Channel and the west tip of the island of Molokai. Most of the heavier rain was moving from south to north across the island of Oahu.

FIGURE 19
GOES-7 SATELLITE PHOTOGRAPH



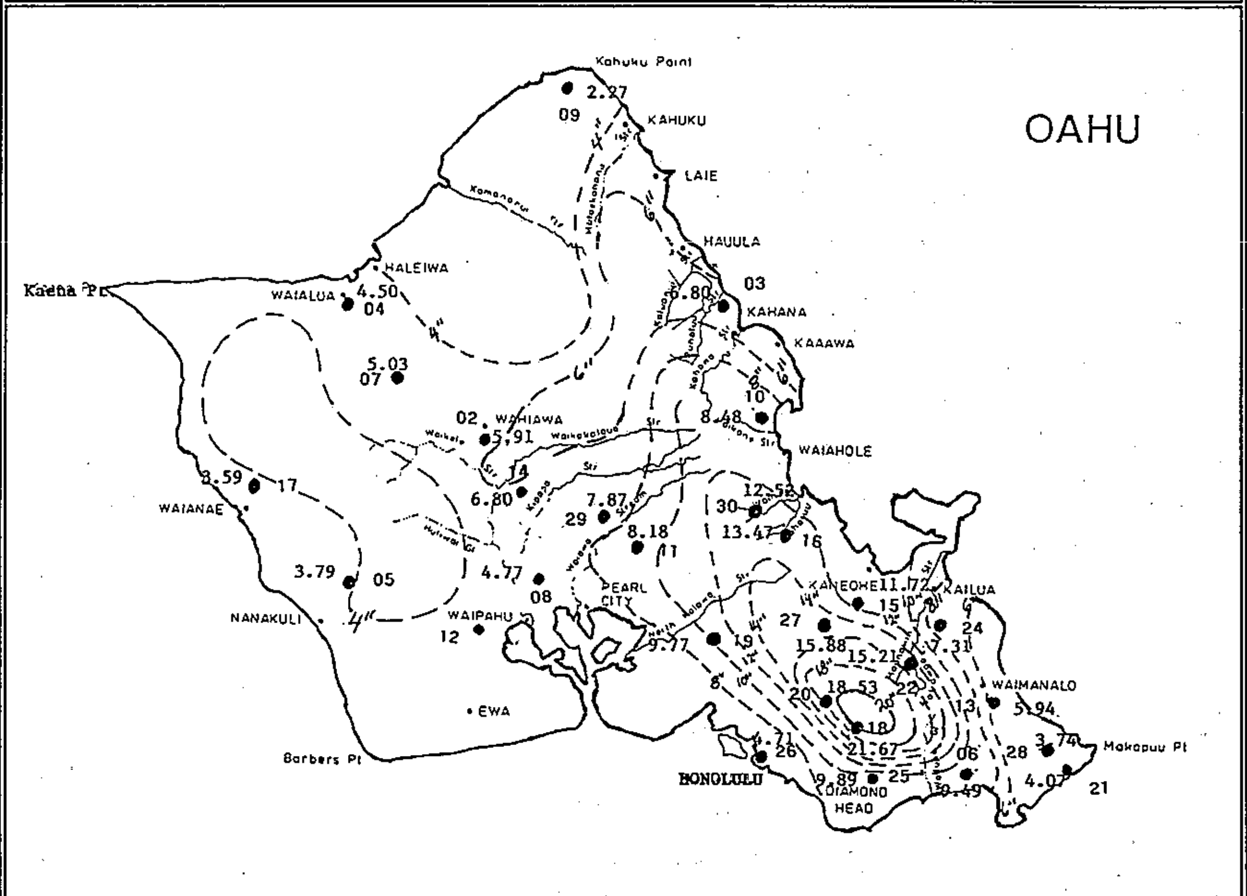
0031 UTC ... MARCH 24, 1994

During this period, the WSR-88D base reflectivity data had pockets of 40-50 Dbz values over the Koolau Range and also in an area 50-100 miles to the south of Oahu.

Rainfall from the island of Molokai east to the Big Island was widely scattered.

Figure 20 is the isohyet analysis of the March 22-25 rainfall, which was recorded by the LARC sites during the upper tropospheric trough event for Oahu. The upper tropospheric trough triggered the release of copious amounts of rain over sections of Oahu. The heaviest totals occurring over the south Koolau Range.

FIGURE 20
MARCH 22-25, 1994 - ISOHYET ANALYSIS



RAINFALL DATA FOR UPPER TROPOSPHERIC TROUGH OVER OAHU

7. SUMMARY

The review of the two 1994 events shows the importance of identifying the trigger of the heavy rainfall. The examination of both cases indicates that there is a definite similarity between both flash flood events. However, a very strong signature that is present during the Kona storm event is the largest contributor to the release of heavy rainfall over leeward sections of all islands. This feature is the low level wind reversal, which is induced when the Kona low develops to the west of Hawaii. In the case of the upper tropospheric trough, a more disorganized precipitation pattern may result as instability pockets rotate around the parent tropospheric trough.

Early detection of the low level wind shift to the south and southwest is certainly the key which forecasters must look for when deciding where the flash flood event will occur. Satellite photographs help to monitor the broad moisture area. However, it is only through the complete understanding of the mesoscale circulations that forecasters are able to focus in on specific areas for the issuance of the flash flood warnings.

The use of the WSR-88D in examining both the Kona Storm and the Upper Tropospheric Trough is what makes this case study unique. WSFO Honolulu has only been receiving WSR-88D since February 1994. During the initial six month period, the radar has been down for an average of 41% of the time. Despite this, much has been learned from using the initial doppler weather radar data sets.

Working with a very limited data set, it has been shown that the precipitation algorithms are underestimating the amount of rainfall over the higher elevations of the Koolau Range, which has its highest peak at 3,150 feet. These initial estimates, which used an extensive LARC network as ground truth data, indicate that for heavy rainfall, the radar is underestimating by as much as 2-4 inches. More investigations will follow in the next few years which will determine if perhaps the depth of the cloud in which warm rain processes operate is not correctly accounted for in the current algorithms.

The base reflectivity and composite reflectivity will be highly utilized in monitoring the windward and mountain showers that are a daily occurrence in the tropics. For the heavy rainfall cases described in this paper, the composite reflectivity product provided a quick and easy way of locating the areas with the highest returns. It was found that there indeed is a high correlation between the quasi-stationary and long duration high composite reflectivity, and heavy rains producing flash flooding. In the February and March cases, using the high composite reflectivity signature for issuance of site specific advisory and warning products would have verified.

The VAD wind profile data for the Molokai WSR-88D is a product which forecasters like and display on a continuous basis. The wind profile is especially useful in identifying the height of the trade wind inversion, and the wind direction and speed are very reliable. It should also play a very important role in providing the forecasters with an early indication of the Kona Storm low level wind shift.

It is definitely a very exciting time for all meteorologists receiving WSR-88D data in the Pacific. Interest in conducting numerous WSR-88D studies has been expressed by the university community and collaborative efforts are currently underway to look at flash flood events, tropical cyclones, high winds, and utilization of the doppler capabilities in wave and swell research.

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Also, I would like to extend my special thanks to the Regional Scientist of the Pacific Region Headquarters, James Partain, Jr., for his critical review. In addition, individuals who provided data for the paper include Karl Turner (Data Acquisition Program Manager), and James Mathison (Senior Service Hydrologist), both from the WSFO in Honolulu.

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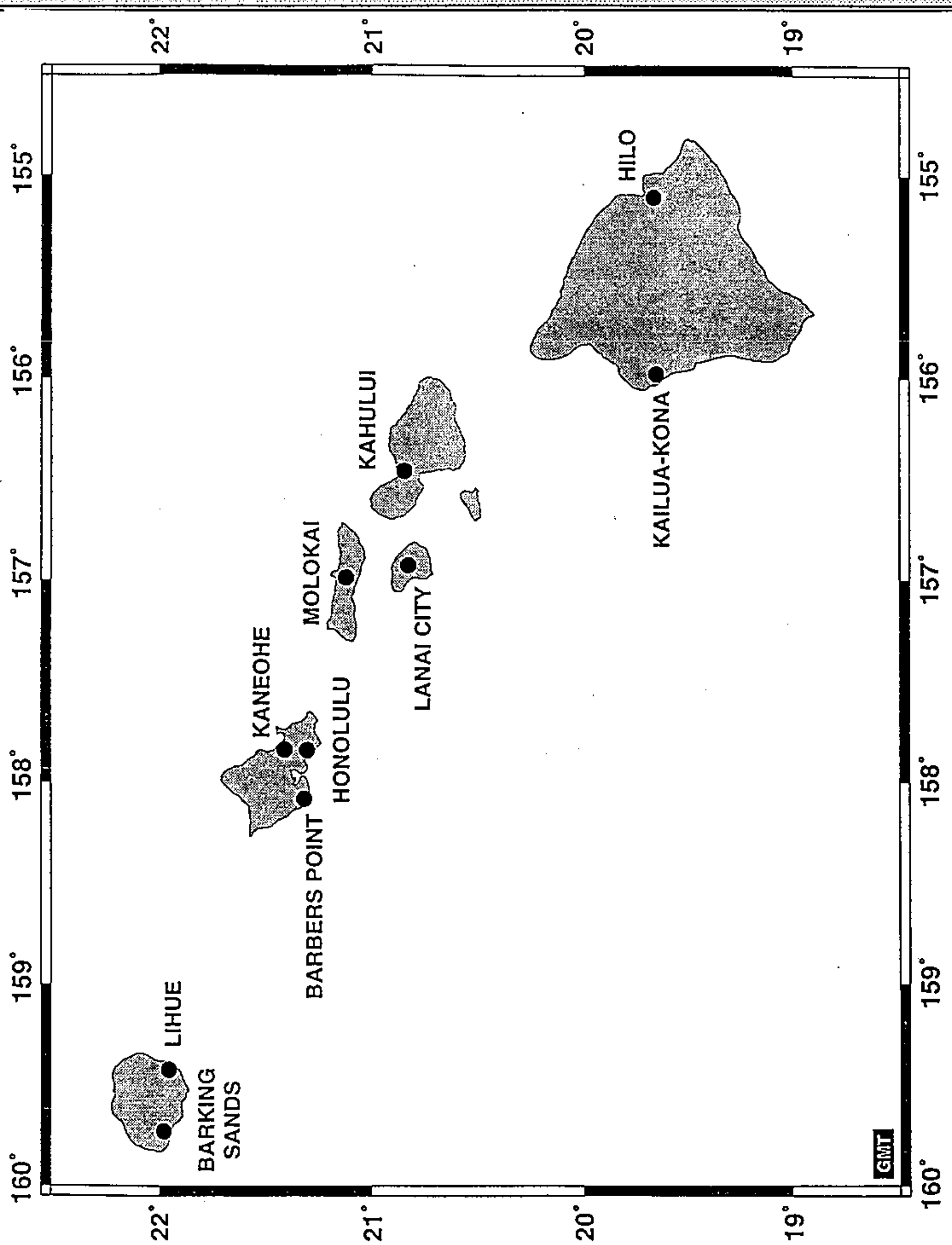
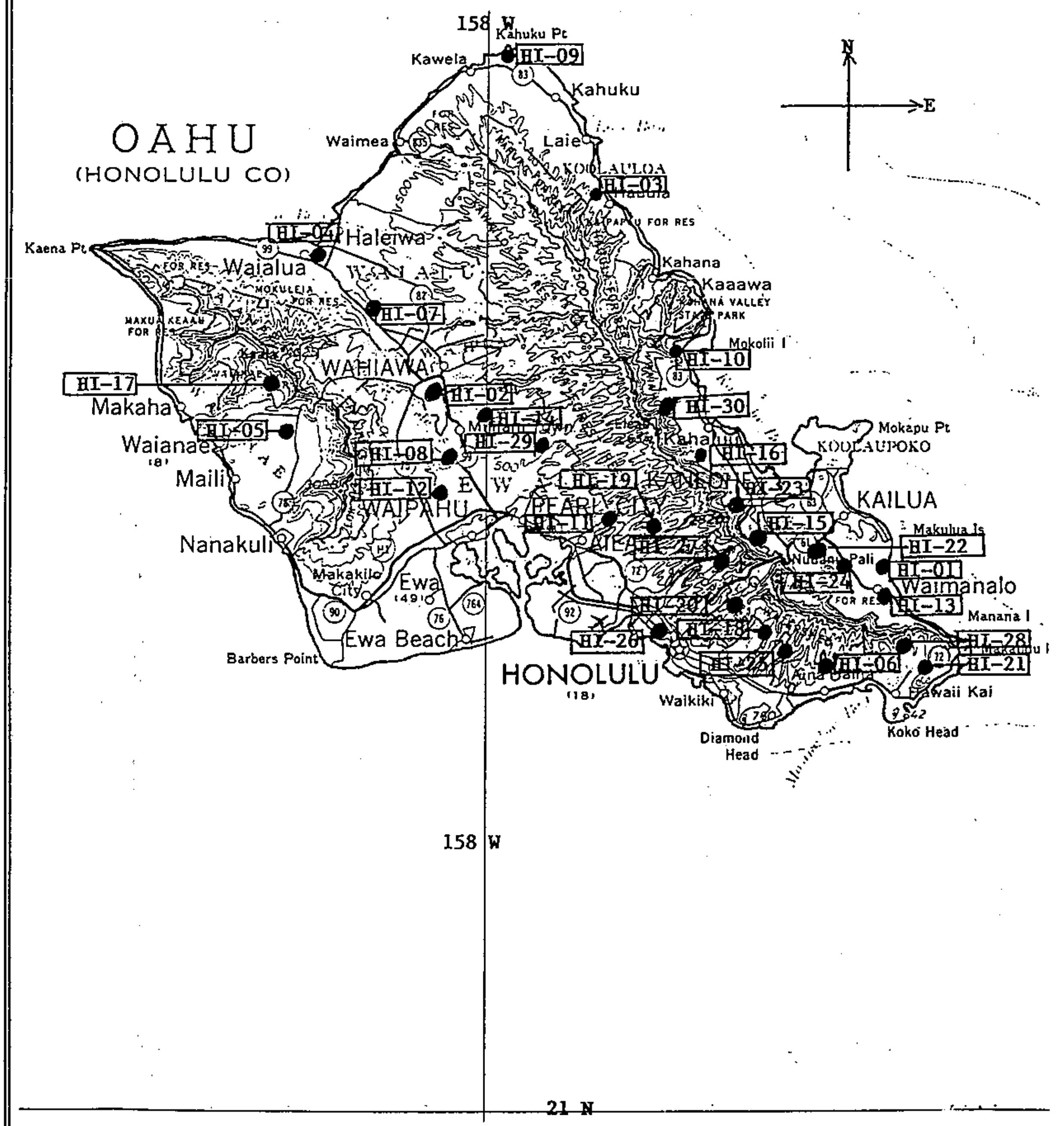
Finally, I would like to express my appreciation to my wife, Norma, who has perhaps been one of the biggest supporters of the science and operations program of the NWS. Her tolerance and acceptance of the long hours spent in research, and her unending encouragement to take on and complete major projects has made life less stressful.

APPENDIX A
REFERENCE MAP OF THE HAWAIIAN ISLANDS



HAWAII

APPENDIX B
OAHU LARC LOCATIONS



OAHU, HAWAII

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